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Department of **Water**

Water-balance modelling of the Leschenault catchment

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Report no. WST 10
August 2009

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Cover photograph: Preston River (Tarren Reitsema)

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1. Introduction

The Leschenault catchment, which drains to the Leschenault Inlet and then the ocean, is located approximately 160 km south of Perth, in the south west of Western Australia. Its area is approximately 2020 km^2 and includes the catchments of the Wellesley, Brunswick, Ferguson and Preston rivers, as well the Collie River catchment below Wellington Reservoir.

Artificial drains have been introduced in the flat coastal plain areas to enable agricultural and urban land uses. The catchment is located within the Collie and Harvey irrigation districts. Harvey Water supplies summer irrigation through an open channel and pipeline network. This has led to a complex hydrological network of drains and natural rivers. Dams located on the Collie, Brunswick and Preston rivers have modified natural flow in the Leschenault catchment.

Although the catchment has a large area of native vegetation in its upper reaches, the land uses on the Swan coastal plain and in the broad river valleys east of the Darling Scarp include cattle raising for beef and dairy, horticulture and viticulture. The population of the catchment is approximately 65 000 (ABS, 2009) with most people living in areas between the lower reaches of the four major rivers and either the coast or the eastern shore of Leschenault Estuary in the towns of Australind and Bunbury.

This modelling project was aimed at quantifying monthly flows for the major rivers located in the Leschenault catchment for the period 1998 to 2007. A new model was developed based on work by Zhang et al. (2005), who developed a simple monthly water-balance model driven by rainfall and potential evaporation. The model developed for the Leschenault catchment incorporated the modified drainage on the coastal plain and irrigation supply in the summer months. Zhang's model was modified to include additional parameters, which account for deep-rooted vegetation and transpiration from the groundwater store.

The flow model has provided the basis for nutrient modelling work in 2009, which involved scenario based modelling of land use changes, improved riparian vegetation management and climate change.

2. The Zhang monthly water-balance model

The monthly water-balance model discussed in Zhang et al. (2005) was modified and used to simulate rainfall-runoff processes for subcatchments within the Leschenault catchment. The model is simple, lumped and conceptual, and operates at a monthly time step. Streamflow is predicted based on three input variables: catchment area, total monthly rainfall (P) and total monthly potential evapotranspiration (E_0).

Zhang's monthly water-balance model is an extension of earlier work (Budyko 1958; Fu 1981; Zhang et al. 2001) that focused on annual timestep equilibrium water-balance modelling, in which water balance is controlled by water availability and atmospheric demand. Several studies have used Zhang's 2001 equation for annual water-balance modelling, including Durrant and Pearcey (2007) in Western Australia. The shift to a monthly timestep introduces storage as an additional model component.

The main functional equation of the model is the relationship between potential and actual evapotranspiration (E) developed by Fu (1981). Figure 2.1 shows the form of the equation, where the ratio of actual evapotranspiration to precipitation (E/P) is related to an index of dryness (E_0/P). The weighting parameter α is related to available water and vegetation water use.

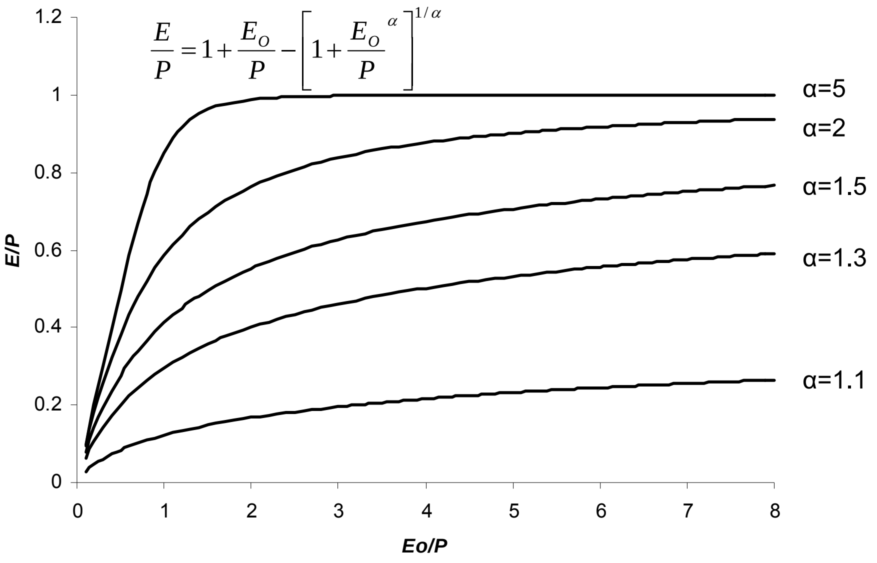


Figure 2.1 After Zhang et al. (2005)

The model partitions rainfall into monthly direct runoff, soil storage and evapotranspiration. Two state variables are introduced in the monthly model: one representing the amount of rainfall available for storage and evapotranspiration, and the other descring the 'evapotranspiration opportunity'. The state variables are used to calculate the direct-runoff, storage, recharge, and water availability. A linear reservoir incorporates groundwater storage and discharge. Evapotranspiration is confined to the unsaturated zone, and groundwater discharge is a linear function of the groundwater store.

This model was calibrated to 11 gauged subcatchments within the Leschenault catchment, for the period January 1998 to December 2007. Irrigation supply volumes were calculated for each subcatchment, and distributed as a uniform irrigation depth across the catchment for model input. Calibration yielded acceptable annual and winter efficiencies; however, summer flows were consistently over-predicted and summer calibration efficiencies were unacceptable.

Analysis of the model showed that there were the following inherent problems when it was applied to the Leschenault catchment:

- Evapotranspiration was confined to the unsaturated zone (the soil moisture store); that is, no evapotranspiration occurred directly from the groundwater store. Therefore, the only way for the groundwater store to decrease was from groundwater discharge. In the shallow groundwater systems of Western Australia, the deep-rooted vegetation draws directly from the groundwater store. Groundwater can also be lost to the deeper aquifers, but this flux is not likely to be large in the Leschenault catchment.
- Groundwater flow is a linear function of the groundwater store, so there is always some groundwater flow as long as the groundwater store is positive (which is all of the time). For most waterways in the Leschenault catchment (the Brunswick being the exception), the groundwater table will drop below the river bed in the summer. In autumn/winter it will recharge with rainfall, and will discharge to the waterway only when the level of the groundwater table is above the river bed level. When the groundwater table drops below the riverbed level the flow in the waterway will cease; hence i.e. the waterway is ephemeral. In the model proposed by Zhang, it is not possible to have a completely ephemeral waterway, so long as the groundwater store is positive.

Modifications were undertaken to partition the evapotranspiration to both the unsaturated and groundwater stores. A critical groundwater level was determined above which groundwater discharge would occur. Groundwater discharge is a linear function of the difference between the level of the groundwater store and the critical groundwater level. Conceptual diagrams of the original model and the altered model are presented in Figure 2.2.

Irrigation runoff and return flows were calculated using a separate module. A proportion of irrigation was assumed to result in direct irrigation return flow for each month. An additional portion of irrigation return flow was assumed to result from soil recharge and through-flow. It was assumed that the remainder was evapotranspired, according to a function of the monthly total evaporation potential E_0. The irrigation module was calibrated for the summer months.

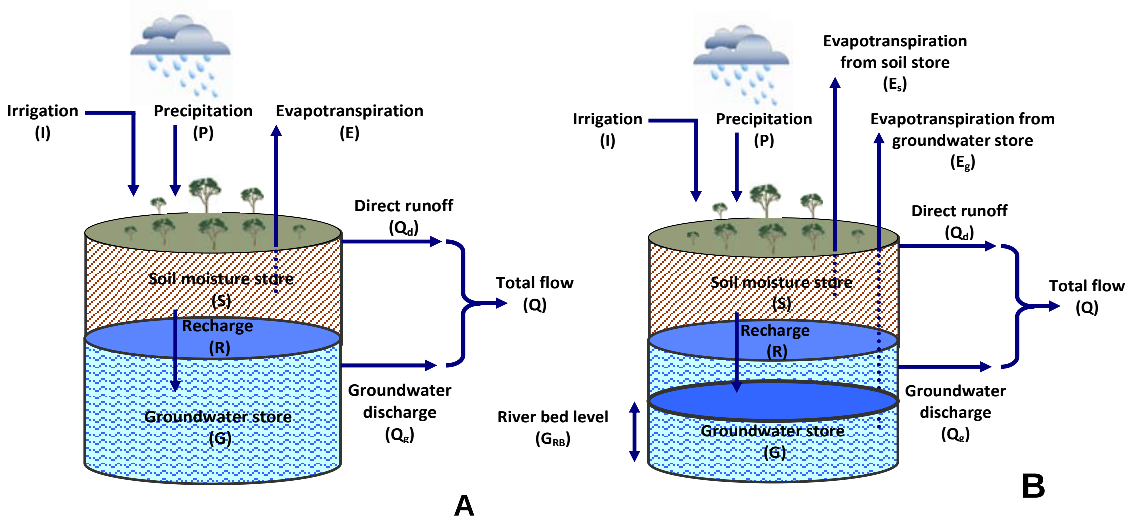


Figure 2.2 Conceptual diagrams of the Zhang (A) and altered (B) models

Calibration of the modified model required four additional parameters and resulted in improved annual and winter efficiencies and acceptable summer efficiencies. Full details of the equations used for modelling are available in Appendix A.

3. Model input

For this study, the monthly model was integrated into a semi-distributed hydrological model using a node-link network. The model was calibrated for each gauged catchment. Once calibrated, the model was used to predict and route flows throughout the Leschenault catchment. No flow lag was applied to stream links as the model is at monthly time step.

3.1 Subcatchment delineation

The Leschenault catchment has modified surface drainage due to remnant and active open-channel water supply channels, Water Corporation drains, and urban drains. A Digital Elevation Model (DEM) with 1 m resolution and 15 cm vertical accuracy was derived from a 2008 LiDAR (Light Detecting and Ranging) survey. Inland of the Darling Scarp, the Land Monitor 10 m pixel resolution DEM was used. A mosaic was generated for the entire Leschenault catchment by combining the LiDAR and Land Monitor datasets, at 3 m pixel resolution. Some additional geo-processing was necessary to ensure the DEM correctly represented surface-water drainage. This included modifying the DEM to burn-in stream and drainage lines, build walls to prohibit flow, and ensure connectivity in streams and drains under roadways.

A number of stream and drainage lines were digitised to align with local minima in elevation identified with the LiDAR dataset. A Water Corporation drainage dataset and the Department of Water’s Linear Hydrography dataset were used as a guide to drain location; however, due to poor horizontal accuracy of features, the drainage dataset for the Leschenault catchment was mostly developed with modified drain positions and new, manually digitised drains.

The resulting dataset was used to burn the drainage network into the 3 m DEM to ensure that water flowed into the correct drainage line when applying a flow accumulation model. Walls were created at key locations within the catchment (e.g. Collie Dam and along the edge of the Harvey Diversion Drain) to prevent water from flowing into incorrect drainage features in the surface-water model. Finally, holes (acting as sinks) were made in the DEM at dam locations so that catchment areas upstream were not considered in catchment delineation.

For model calibration, 13 subcatchments were delineated based on Department of Water gauge locations. The final subcatchments are shown in Figure 3.1, and catchment/gauge details are outlined in Table 3.1.

The locations of subcatchments are fixed by the location of flow gauges. This is a requirement for model calibration. Alternative catchment boundaries are possible for reporting purposes but have not been included in this version of the model.

Note that the subcatchments defined in this project differ slightly from those in the recent Catchment Management Support System (CMSS) modelling conducted by the Department of Water (Kelsey 2009). Estuary and coastal catchments were not included. The Upper Brunswick, Ferguson and Mid Preston have been split into two subcatchments each for the current modelling.

Table 3.1 Subcatchment summary details.

Gauge ID	Gauge name	Catchment name	Veg** %	Area (km^2)	Calibrated
611004	BOYANUP BRIDGE	Mid Preston	64%	186	Yes
611006	DONNYBROOK	Preston - Donnybrook	44%	195	Yes
611007	SW HWY FERGUSON	Lower Ferguson	7%	23	No
611009	LOWDEN ROAD BRIDGE	Upper Preston	72%	289	Yes
611010	MOONLIGHT BRIDGE	Lower Preston	27%	164	No
611017	DOUDELL ROAD BRIDGE	Upper Ferguson	62%	114	Yes
611111	WOODPERRY HOMESTEAD	Thomson Brook	75%	102	Yes
612022	SANDALWOOD	Brunswick Upper 2	90%	117	Yes
612032	CROSS FARM	Mid Brunswick	35%	98	Yes
612039	JUEGENUP WELLESLEY	Wellesley	18%	199	Yes
612043	ROSE ROAD	Collie Lower 2*	16%	83	Yes
612046	EATON FORESHORE	Collie Lower 1	21%	164	No
612047	BEELA	Brunswick Upper 1	67%	93	Yes

**excludes area upstream of Burekup Weir on the Collie River*

***defined as percentage deep rooted vegetation within the catchment, including plantation*

Figure 3.1 Leschenault subcatchment boundaries

3.2 Climate time-series

SILO (BOM, 2008) patched point data was used as time-series input data for the model. Several processing steps were conducted to generate monthly time-series of E_0 and P for each subcatchment. For each month between 1 January 1998 and 12 December 2007, the SILO point estimates of monthly total rainfall and pan evaporation were interpolated to generate climate surfaces using discretised splines. At each timestep, the average value of the surface was calculated across each subcatchment to generate a new time-series representative of the entire area.

3.3 Irrigation time-series

Harvey Water provided monthly irrigation data (1998–2007) at all supply points within the Harvey Water irrigation supply areas. The total monthly volume of water supplied for irrigation (as billed at the end of each month) was summed for supply points located within each subcatchment. It was assumed that the calculated volume of water was distributed evenly across the catchment, and an average depth (mm) of irrigation was then calculated. The monthly irrigation depth was combined with monthly rainfall as input into the water-balance model. Figure 3.2 shows the distribution of irrigation supply points used to calculate monthly irrigation supplied.

The Preston Valley Irrigation Cooperative (PVIC) provided monthly irrigation release data (1998–2007) for the Glen Mervyn Dam on the Upper Preston. It was assumed that this irrigation supply was evenly distributed in the Upper Preston catchment.

3.4 Flow time-series

Within the Leschenault catchment there are 13 gauges with sufficient length of record to calibrate the model. Time-series data of streamflow was extracted from the Department of Water’s Hydstra database. Where possible, the length of record covered the same period as the climatic data; however, for some gauges, data infilling was conducted using nearby gauge data and regression analysis. Two gauges that were used for catchment delineation could not be used for calibration because they were located in the Leschenault Estuary (612046 and 611010), and therefore affected tidally. A third gauge on the Ferguson (611007) could not be used for calibration as the record was inaccurate.

Where catchments were located downstream (had upstream gauged subcatchments), the observed upstream flow time-series was subtracted from the measured flow before calibration of the rainfall-runoff model. Where upstream flows exceeded downstream flows, observed flow was set to zero.

3.5 Burekup Weir releases and Wellington Dam overflow

The Burekup Weir is used to divert water into the Collie open-channel irrigation network. The weir significantly modifies flow in the lower Collie River despite having a relatively small storage capacity. Harvey Water is required to release water over the summer period to match historic flows resulting from dam leakage. The Water Corporation provided approximate water-balances for the Burekup Weir. These were used to estimate monthly dam releases from the Burekup Weir for 1998 to 2007.

Releases from Wellington Dam were accurately captured by the Collie Flume gauge (612013), but there was no data available for inflows to the Burekup Weir. As a result, the Collie River catchment upstream of Burekup Weir was not calibrated. Water released from the Wellington Dam has been included in total water budget through the irrigation supply data and Burekup Weir release estimates.

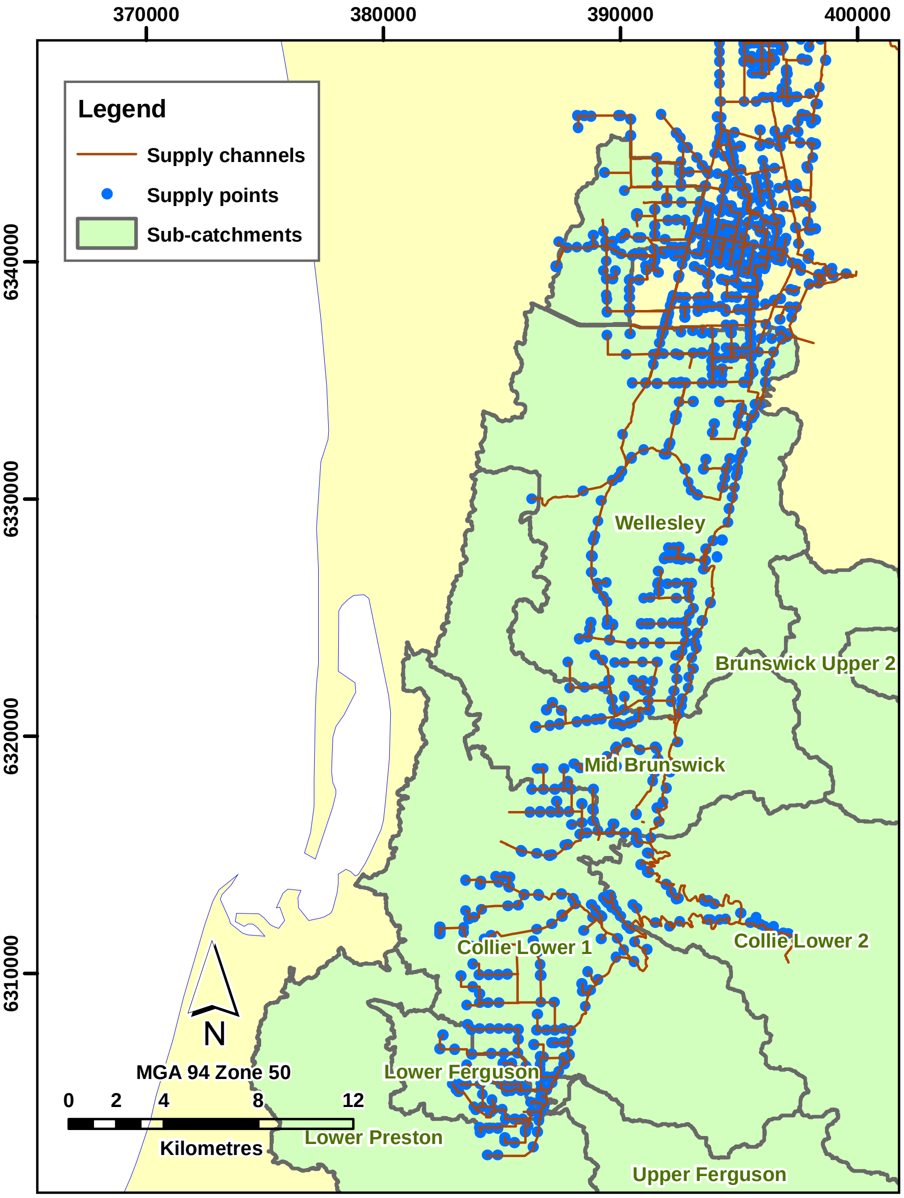


Figure 3.2 Irrigation supply points in the Leschenault catchment

4. Calibration and model results for individual catchments

Each of the Leschenault subcatchments was calibrated independently. The Nash-Sutcliffe coefficient of efficiency (ε) (see Appendix A) was used as the objective function for calibration and the key indicator of model performance. Optimisation of the model was performed using the solver function in Microsoft Excel ^{tm} 2003 and a genetic algorithm developed by Turkkan (2006). Each subcatchment was manually calibrated and checked to ensure model parameters and modelled hydrographs represented observed subcatchment behaviour and characteristics (particularly summer low-flows and groundwater storage/discharge). Results of model calibration, associated issues and a summary of flow statistics are discussed for each subcatchment below.

Subcatchments within the Collie River catchment area (Brunswick, Wellesley and Collie rivers) are discussed first, then subcatchments draining to the Preston River (Ferguson and Preston rivers).

See the notes below on reporting of statistics for the following sections:

- discharge summaries are based on modelled figures
- unless otherwise specified, winter refers to the period May to October, and summer the period November to April
- measurements in mm indicate water yield per catchment: this allows comparison of discharge in catchments with different areas; for example, 2 mm of discharge in a 100 km^2 catchment is equal to 200 ML
- the Nash-Sutcliffe coefficient of efficiency is referred to as efficiency or just ε.
- error statistics are not reported for subcatchments with no calibration data
- one-year warm-up period was used for model calibration.

4.1 Brunswick Upper 2 (612022)

The Brunswick Upper 2 catchment is located in the headwater of the Brunswick River, and is 91 per cent covered by native vegetation.

This catchment contains the Worsley Dam, which as a minimum releases 35 kL/hour of water during summer to maintain summer low-flows (DoW 2008). Before calibration, this additional flow was removed from the downstream observed flow.

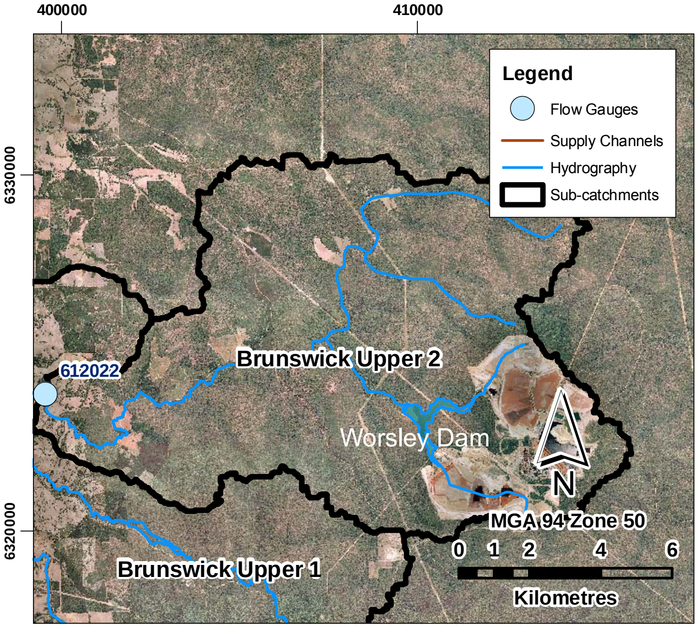


Figure 4.1 Brunswick Upper 2 catchment

Model calibration and results are included in a summary sheet on the following page (Figure 4.2).

Efficiency (ε) of 0.72 indicates moderate model performance, with best model fit for non-peak flows. The model under-estimates peak flows slightly. The 10 year average annual discharge is under-predicted by 4 per cent, which can be attributed to under-prediction in the winters of 2002 and 2003, or possibly to the presence of Worsley Dam, which may overflow or release water in wet years – a process not accounted for in the model.

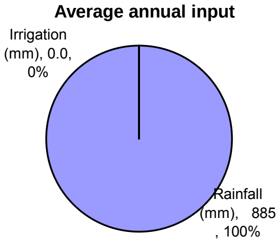
The catchment does not dry completely during summer, with runoff averaging just under 4 mm. There is some groundwater discharge year round in all but the driest two years modelled (2001 and 2007).

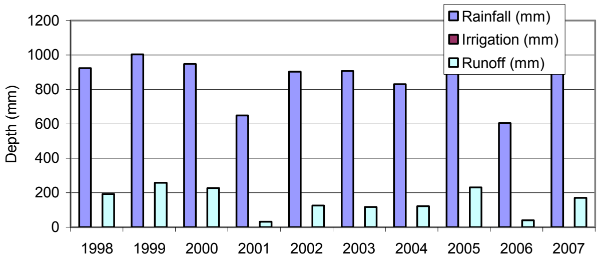
Average monthly statistics (modelled)

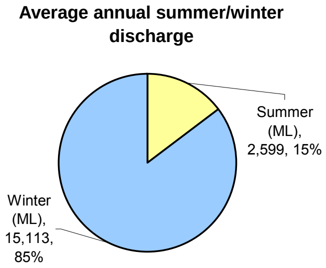
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	15	0.0	5.6	650
February	5	0.0	1.9	223
March	23	0.0	1.3	152
April	40	0.0	0.8	89
May	114	0.0	4.0	467
June	151	0.0	12.9	1 511
July	158	0.0	25.1	2 941
August	166	0.0	44.4	5 191
September	109	0.0	29.2	3 422
October	60	0.0	13.5	1 581
November	29	0.0	8.3	975
December	14	0.0	4.4	509

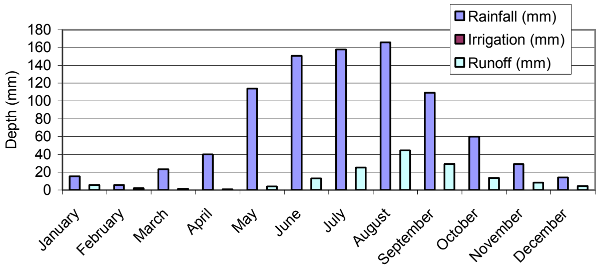
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	924	0.0	193	22 534
1999	1 004	0.0	258	30 230
2000	949	0.0	227	26 524
2001	648	0.0	31	3 578
2002	904	0.0	126	14 706
2003	907	0.0	117	13 695
2004	831	0.0	121	14 193
2005	1 073	0.0	231	26 997
2006	603	0.0	40	4 718
2007	1 009	0.0	170	19 942
Average	885	0.0	151	17 712



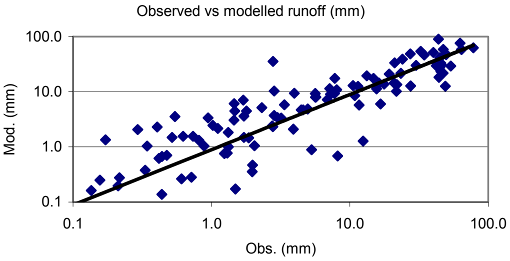






Nash-Sutcliffe Efficiency: *E*	0.72
Obs. avg. annual runoff (mm)	158
Mod. avg. annual runoff (mm)	151
Difference:	-3.90%
Summer RMSE	4.76
Winter RMSE:	12.70
Mean summer runoff (Nov-Apr) (mm)	22
Mean summer discharge (Nov-Apr) (ML)	2,599
Mean winter runoff (May-Oct) (mm)	129
Mean winter discharge (May-Oct) (ML)	15,113
Discharge % of inputs (average)	17%
Discharge % of inputs (dry 2006)	7%
Discharge % of inputs (wet 1999)	26%

Modelled data



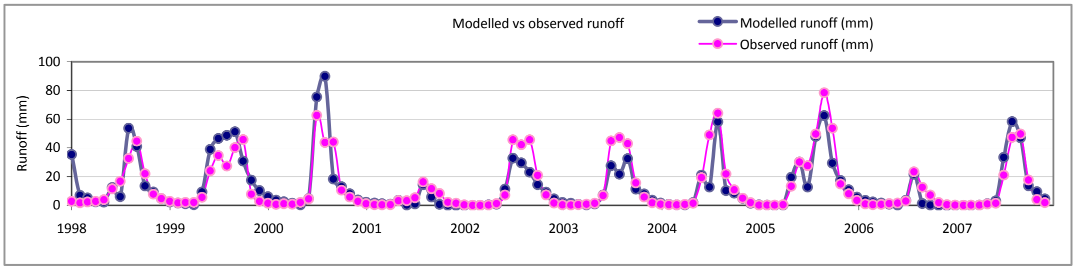


Figure 4.2 Brunswick Upper 2 – calibration results and summary statistics

4.2 Brunswick Upper 1 (612047)

The Brunswick Upper 1 catchment is located on the Darling Scarp, immediately downstream of the Brunswick Upper 2 catchment. It is partially vegetated (66 per cent).

The Beela gauge (612047) associated with Brunswick Upper 1 was identified as erroneous when the flow time-series was compared with upstream and downstream gauges. The flow recorded at this gauge (mm) was consistently higher than the next downstream gauge (612032) and all other vegetated scarp catchments. The recorded flow at Beela was reduced using linear regression with the upstream gauge 612022 and consideration of the downstream gauge at 612032. Modification of the flow time-series makes logical and physical sense, and was necessary for model calibration. Work by Annan (2006) indicated this section of the Brunswick and the reach upstream of 612032 were both gaining reaches, so the inconsistencies between upstream and downstream gauges could not be attributed to groundwater recharge.

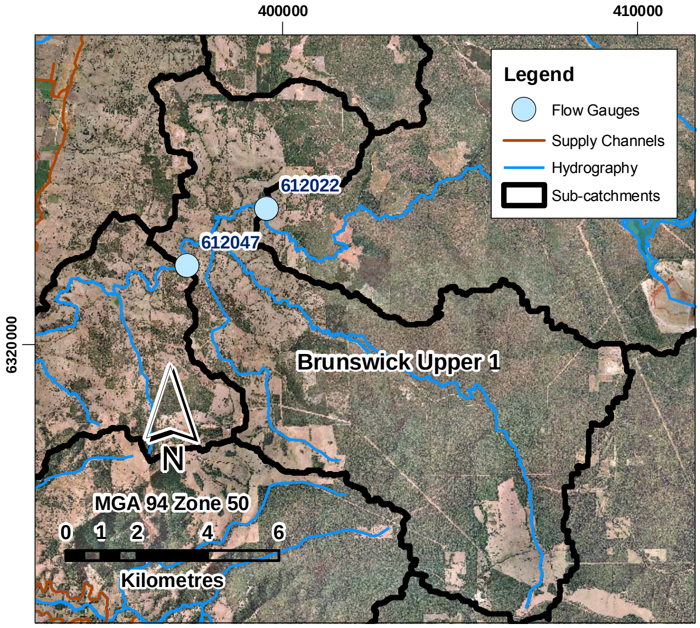


Figure 4.3 Brunswick Upper 1 catchment

After time-series modification, the Brunswick Upper 1 catchment calibrated moderately well, with an ε of 0.69, and a close fit between observed and modelled flow time-series. The average annual flow over a 10 year period was under-predicted by 11 per cent. Modelled summer and winter flows matched observed data closely.

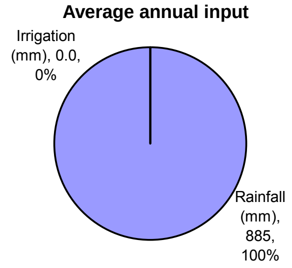
The Brunswick Upper 1 exhibits drier hydrological behaviour than the Brunswick Upper 2, with an almost complete drying of the catchment in summer, and very low groundwater discharge in dry winters. Summer base-flows are consistently below 1mm. Summary data is shown on the following page in Figure 4.4.

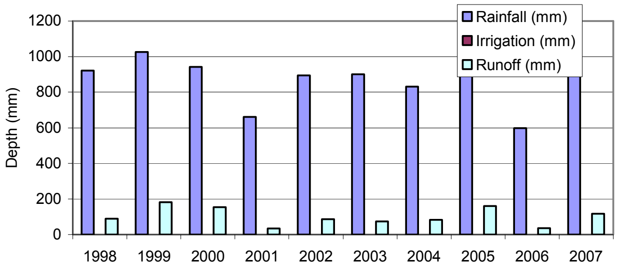
Average monthly statistics (modelled)

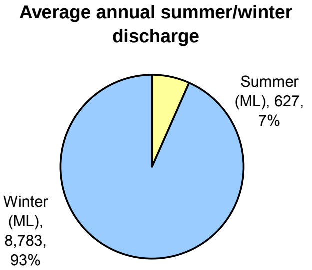
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	15	0.0	0.6	52
February	6	0.0	0.2	17
March	24	0.0	0.3	24
April	40	0.0	0.3	32
May	114	0.0	5.4	505
June	151	0.0	13.4	1 244
July	159	0.0	20.1	1 873
August	166	0.0	29.3	2 723
September	108	0.0	18.8	1 749
October	58	0.0	7.4	687
November	29	0.0	3.8	353
December	14	0.0	1.6	149

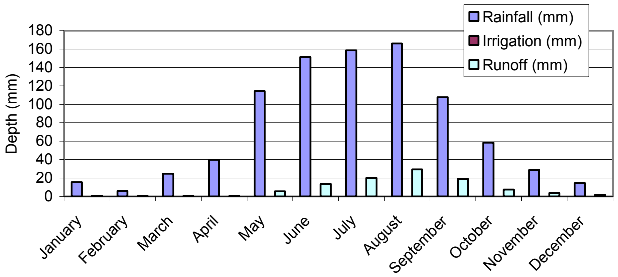
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	921	0.0	89	8 251
1999	1 026	0.0	181	16 873
2000	943	0.0	153	14 275
2001	661	0.0	34	3 120
2002	894	0.0	86	8 025
2003	901	0.0	73	6 798
2004	832	0.0	82	7 645
2005	1 063	0.0	159	14 818
2006	599	0.0	36	3 366
2007	1 010	0.0	117	10 920
Average	885	0.0	101	9 409

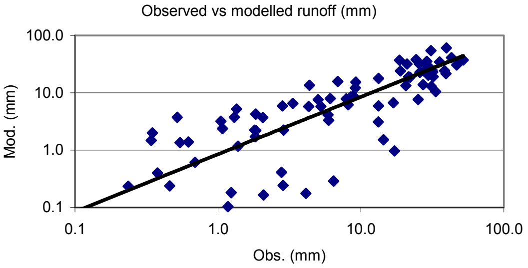








Nash-Sutcliffe Efficiency: ***E***	0.69	
Obs. avg. annual runoff (mm)	114	
Mod. avg. annual runoff (mm)	101	
Difference:	-11.28%	
Summer RMSE	1.48	
Winter RMSE:	9.18	
Mean summer runoff (Nov-Apr) (mm)	7	**Modelled data**
Mean summer discharge (Nov-Apr) (ML)	627	
Mean winter runoff (May-Oct) (mm)	94	
Mean winter discharge (May-Oct) (ML)	8,783	
Discharge % of inputs (average)	11%	
Discharge % of inputs (dry 2006)	6%	
Discharge % of inputs (wet 1999)	18%	



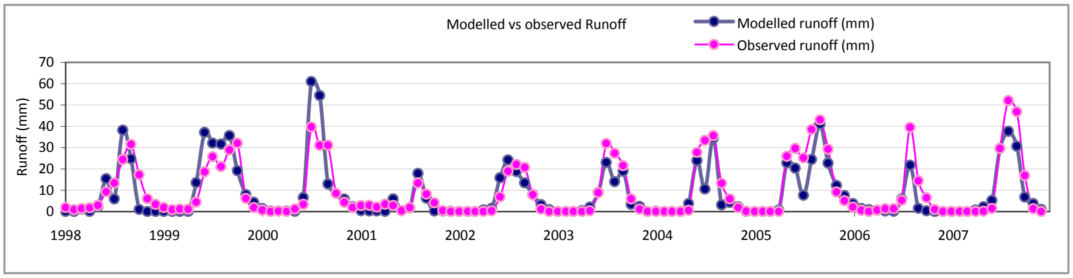


Figure 4.4 Brunswick Upper 1 – calibration results and summary statistics

4.3 Wellesley (612039)

The Wellesley catchment is located on the Swan coastal plain in the headwater of the Wellesley River. For the period 1998 to 2007 it received significant irrigation during the summer months, averaging 94 mm (18 630 ML) per irrigation season, which was the highest total irrigation volume of all subcatchments. The catchment has a complex supply channel network that provides irrigation water. It also has modified drainage, particularly in the northern part of the catchment where the Wellesley River crosses the Harvey diversion drain. The catchment area has been reduced slightly with the revised catchment delineation (compared with the original boundary defined by the Department of Water).

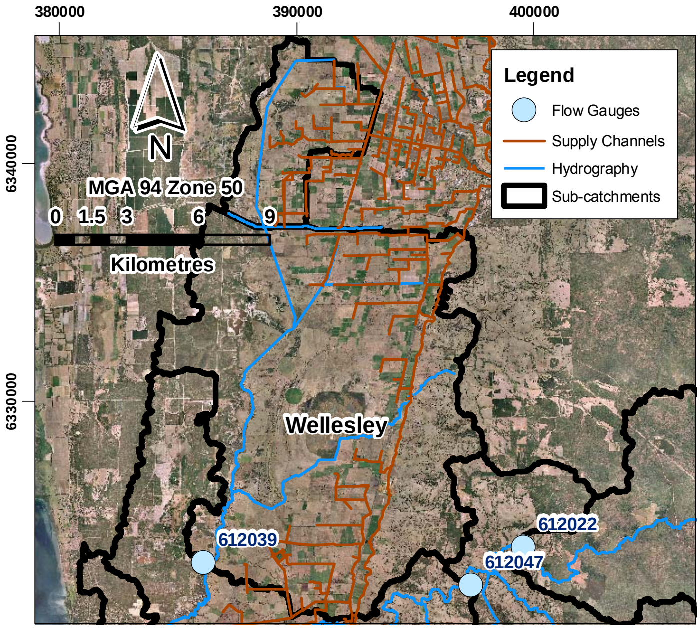


Figure 4.5 Wellesley catchment

Modelled discharge closely matched observed data for the Wellesley (ε = 0.91), as can be seen in Figure 4.6 on the following page. Summer low flows resulting from irrigation, and winter peak flows closely matched observed data. Summer flows were significant, totalling 12 per cent of annual runoff on average, and averaging 5 mm per month (November to April).

The Wellesley catchment contributed the greatest volume of water to the Leschenault Estuary when compared with all other subcatchments at 50 212 ML, or 19 per cent of total inflows (see Figure 5.7). It is a relatively wet catchment, with discharge totalling 14 per cent of rainfall and irrigation inputs even in a dry year. The high relative wetness can be attributed to vegetation clearing and summer irrigation.

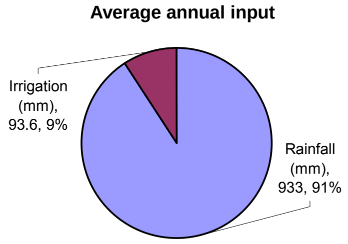
There was a problem with gauged data in 2007 (see Figure 4.6); it shows significantly lower flow than would reasonably be expected, and does not match observed flows in the immediate downstream gauge (612032).

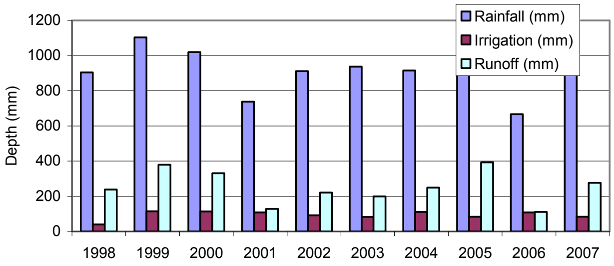
Average monthly statistics (modelled)

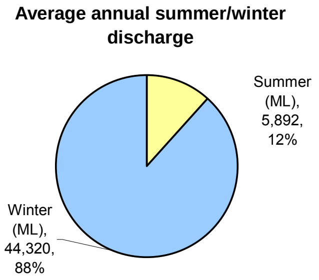
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	34	18.5	5.8	1 157
February	22	16.3	4.3	865
March	40	16.7	4.5	903
April	46	6.5	2.0	405
May	111	0.5	11.8	2 341
June	149	0.4	39.5	7 863
July	152	0.0	60.1	11 956
August	151	0.0	69.9	13 911
September	101	0.1	32.2	6 405
October	54	2.4	9.3	1 843
November	42	14.0	7.2	1 441
December	31	18.2	5.6	1 123

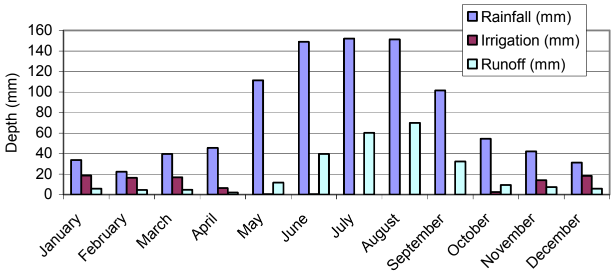
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	904	40.3	239	47 463
1999	1 103	114.4	379	75 354
2000	1 020	112.9	332	65 999
2001	738	108.7	128	25 472
2002	911	90.9	221	43 911
2003	937	82.4	198	39 418
2004	916	110.3	249	49 508
2005	1 136	83.7	393	78 117
2006	666	108.5	110	21 933
2007	1 003	84.0	276	54 949
Average	933	93.6	252	50 212



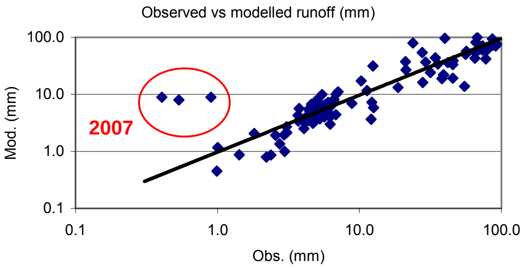






Nash-Sutcliffe Efficiency: ***E***	0.91
Obs. avg. annual runoff (mm)	251
Mod. avg. annual runoff (mm)	252
Difference:	-7.39%
Summer RMSE	1.84
Winter RMSE:	12.84
Mean summer runoff (Nov-Apr) (mm)	30
Mean summer discharge (Nov-Apr) (ML)	5,892
Mean winter runoff (May-Oct) (mm)	223
Mean winter discharge (May-Oct) (ML)	44,320
Discharge % of inputs (average)	25%
Discharge % of inputs (dry 2006)	14%
Discharge % of inputs (wet 1999)	31%

Modelled data



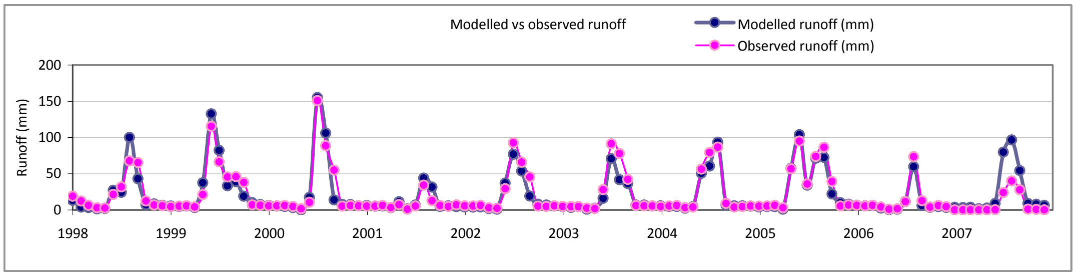


Figure 4.6 Wellesley – calibration results and summary statistics

4.4 Mid Brunswick (612032)

The Mid Brunswick catchment is located on the Swan coastal plain, downstream of the Wellesley and upper Brunswick catchments. It receives significant summer irrigation (63 mm; 6,200 ML on average) and behaves in a similar hydrologic fashion to the Wellesley catchment. Summer flow due to irrigation averages 4.5 mm/month, making up 15 per cent of total annual flows. The catchment is relatively wet, with discharge totalling between 13 per cent and 25 per cent of combined rainfall and irrigation for the period 1998 to 2007.

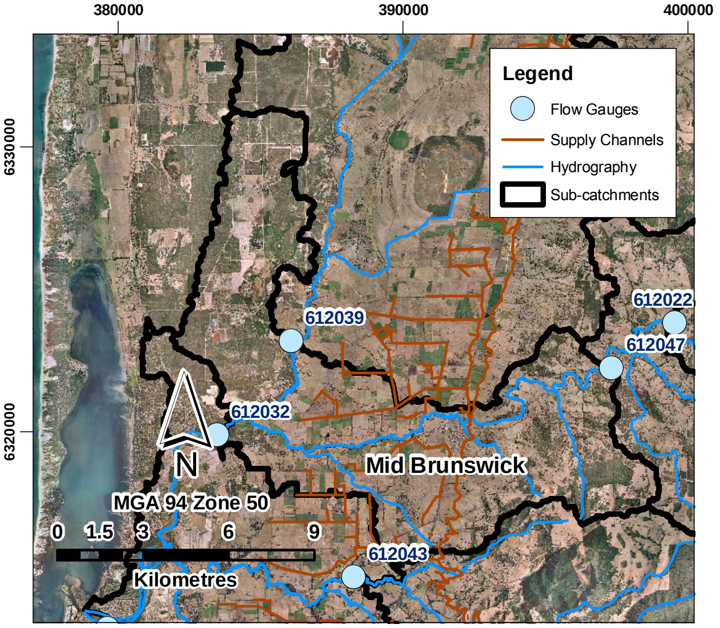


Figure 4.7 Mid Brunswick catchment

As this catchment is located downstream of two catchments, gauge errors are compounded, making the observed time-series less reliable than for headwater catchments. These errors are most apparent in summer discharges. The problems with observed data have resulted in a low value of $\varepsilon = 0.61$; however, the modelled catchment behaviour is more realistic than implied by this statistic.

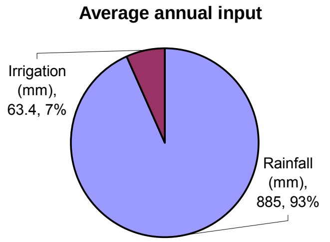
Gauge 612047 on the Brunswick River was modified as described previously. The model reproduced observed values with reasonable accuracy for the majority of years (see Figure 4.8). Modelled upstream flows from the Wellesley were used for 2007 to limit the influence of upstream gauge errors in that year.

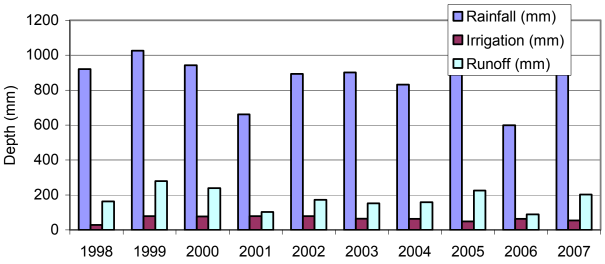
Average monthly statistics (modelled)

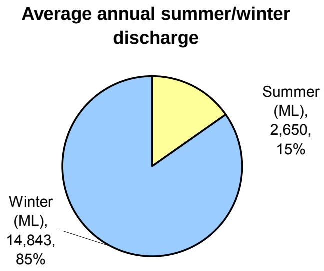
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	15	12.4	4.4	436
February	6	11.3	4.5	438
March	24	10.6	4.8	474
April	40	3.6	3.1	302
May	114	0.4	10.8	1 056
June	151	0.2	23.8	2 334
July	159	0.0	34.4	3 370
August	166	0.0	47.4	4 643
September	108	0.1	27.0	2 641
October	58	1.9	8.2	799
November	29	10.4	5.4	527
December	14	12.5	4.8	472

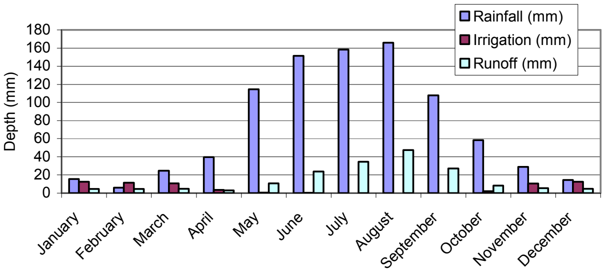
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	921	28.4	164	16 083
1999	1 026	78.4	280	27 411
2000	943	77.7	239	23 466
2001	661	78.7	103	10 124
2002	894	78.0	173	16 962
2003	901	64.2	151	14 831
2004	832	62.8	158	15 505
2005	1 063	48.8	226	22 127
2006	599	62.6	88	8 666
2007	1 010	54.6	202	19 748
Average	885	63.4	178	17 492

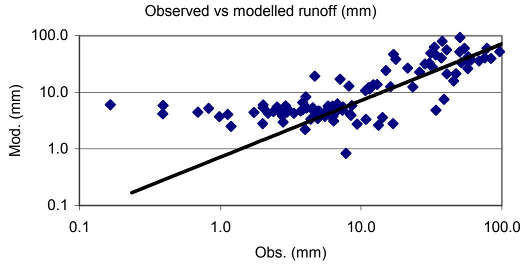








Nash-Sutcliffe Efficiency: ***E***	0.61	
Obs. avg. annual runoff (mm)	198	
Mod. avg. annual runoff (mm)	178	
Difference:	-4.59%	
Summer RMSE	3.59	
Winter RMSE:	17.57	
Mean summer runoff (Nov-Apr) (mm)	27	**Modelled data**
Mean summer discharge (Nov-Apr) (ML)	2,650	
Mean winter runoff (May-Oct) (mm)	151	
Mean winter discharge (May-Oct) (ML)	14,843	
Discharge % of inputs (average)	19%	
Discharge % of inputs (dry 2006)	13%	
Discharge % of inputs (wet 1999)	25%	



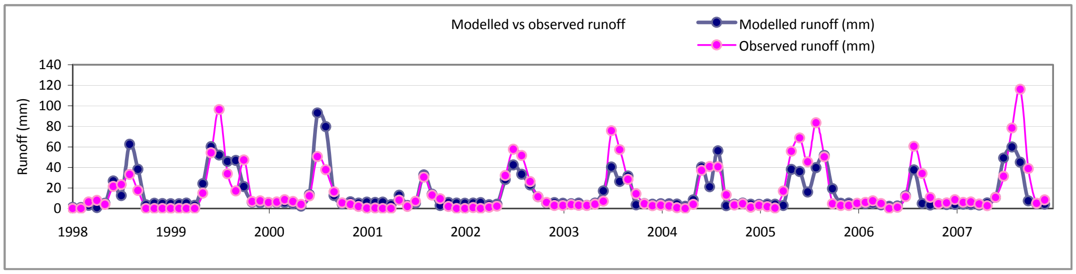


Figure 4.8 Mid Brunswick – calibration results and summary statistics

4.5 Collie Lower 2 (612043)

The Collie Lower 2 catchment includes the area downstream of the Wellington Dam. The catchment is dammed at Burekup Weir, which is located at the edge of the forested upper portion of the catchment. The weir is used to divert water into the Harvey Water irrigation supply channels. Only areas downstream of the Burekup Weir were modelled – reducing the catchment area to 83km^2. This was necessary because no continuous gauge records were available at the inflow of Burekup Weir. The upper reaches of the catchment were not included in the model.

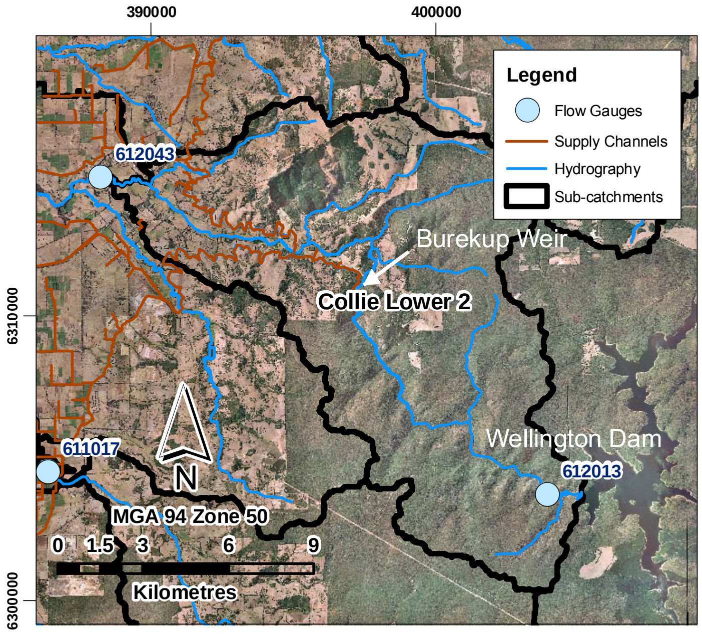


Figure 4.9 Collie Lower 2 catchment

The Water Corporation provided monthly dam release figures from the Burekup Weir. These were used to modify the observed discharge data at 612043 (used in model calibration). The approximate nature of the Water Corporation calculations introduced uncertainty into the observed discharge time-series. The years 1998 to 2000 were excluded from model calibration and error statistics as the observed time-series was deemed unrealistic. After time-series modification, the model calibrated well, with a high ε of 0.92. Modelled average annual discharge was under-predicted by 7 per cent; however, this was associated with observed summer flows, most likely due to dam releases not accounted for in the Water Corporation data from Burekup Weir.

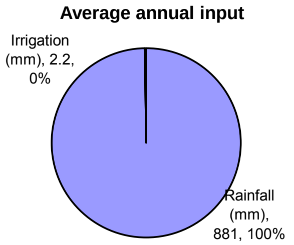
The catchment is relatively wet compared with others in the Darling Scarp, with discharge equal to between 14 per cent and 38 per cent of rainfall over the 10 year period modelled. As only the lower, cleared portion of the catchment was modelled the wetness may be attributed to the absence of deep-rooted vegetation. Groundwater discharge from aquifers may also contribute to catchment discharge. There are several irrigated properties in the lower catchment, but average annual irrigation is only 2 mm, which would make little difference to the hydrology of the catchment.

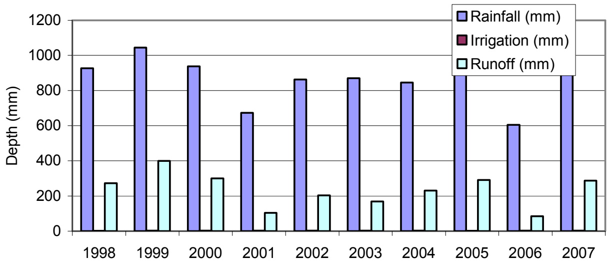
Average monthly statistics (modelled)

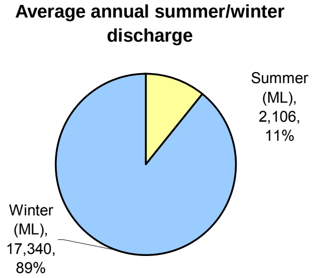
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	15	0.5	5.7	471
February	7	0.4	1.3	112
March	25	0.4	0.9	71
April	40	0.1	0.6	50
May	113	0.0	7.3	605
June	150	0.0	25.8	2 139
July	159	0.0	46.6	3 865
August	167	0.0	68.5	5 689
September	105	0.0	40.5	3 363
October	56	0.0	20.2	1 679
November	28	0.3	11.2	929
December	15	0.4	5.7	473

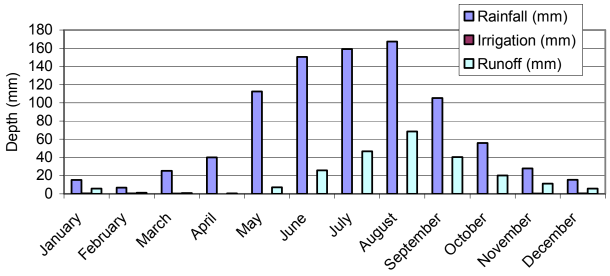
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	928	0.9	273	22 649
1999	1 044	2.5	399	33 124
2000	937	2.3	300	24 890
2001	673	2.9	104	8 646
2002	862	2.6	204	16 935
2003	871	2.2	169	14 050
2004	846	2.7	230	19 122
2005	1 036	1.9	291	24 182
2006	605	2.2	85	7 080
2007	1 010	2.3	287	23 782
Average	881	2.2	234	19 446



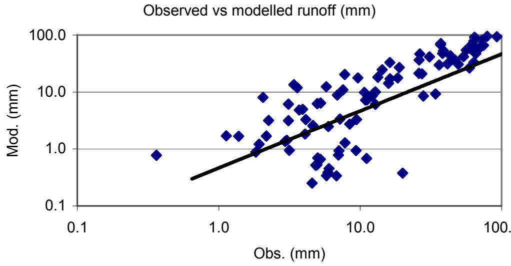






Nash-Sutcliffe Efficiency: ***E***	0.92
Obs. avg. annual runoff (mm)	303
Mod. avg. annual runoff (mm)	234
Difference:	-7.14%
Summer RMSE	6.09
Winter RMSE:	50.34
Mean summer runoff (Nov-Apr) (mm)	25
Mean summer discharge (Nov-Apr) (ML)	2,106
Mean winter runoff (May-Oct) (mm)	209
Mean winter discharge (May-Oct) (ML)	17,340
Discharge % of inputs (average)	27%
Discharge % of inputs (dry 2006)	14%
Discharge % of inputs (wet 1999)	38%

Modelled data



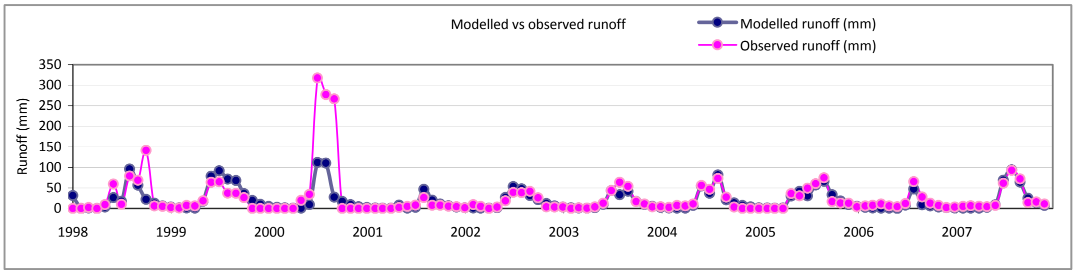


Figure 4.10 Collie Lower 2 – calibration results and summary statistics

4.6 Collie Lower 1 (612046)

Most of the Collie Lower 1 catchment is located on the Swan coastal plain, with a portion downstream of the Brunswick/Collie confluence, and it discharges into the Leschenault Estuary. Some small pockets of native vegetation occur in the upper portion of the catchment, located in the Darling Scarp, although these constitute only 21 per cent of the total catchment area; the remainder has been cleared for agriculture or urban developments.

The gauge associated with this catchment is located in the estuary, and is tidally influenced, so could not be used for model calibration or calculation of error statistics. As such, the parameters calibrated for the Wellesley were used for Collie Lower 1. The transfer of model parameters was justified because both catchments are on the coastal plain, have modified drainage and summer irrigation, and are mostly cleared.

The Collie Lower 1 catchment received the third-highest volume of irrigation in the Leschenault area, with average annual inflows of 10 897 ML (or 66 mm depth) across the catchment each year.

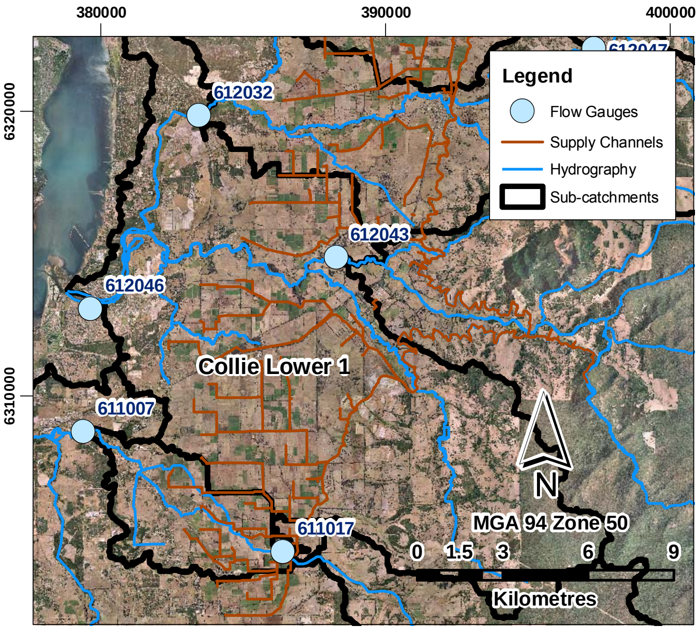


Figure 4.11 Collie Lower 1 catchment

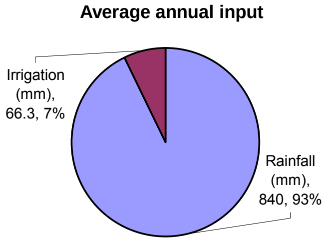
Modelled discharge from Collie Lower 1 is similar to that of the Wellesley, as a result of identical parameter sets, although distinct time-series of hydrological drivers (evaporation, rainfall and irrigation) were used. Summer low-flows associated with irrigation average 4 mm/month, with summer flows totalling 9 per cent of average annual flows. The catchment is relatively wet, with annual discharge varying between 19 and 41 per cent as a proportion of rainfall and irrigation. See Figure 4.12 for complete statistics.

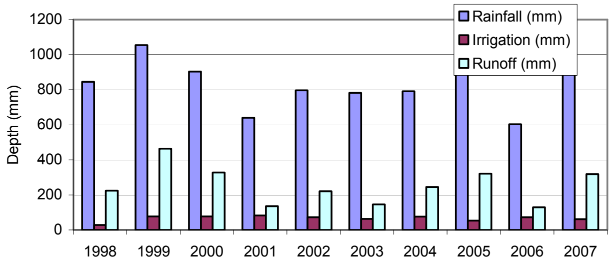
Average monthly statistics (modelled)

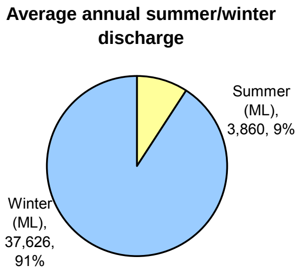
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	16	13.2	4.4	729
February	7	11.9	3.3	546
March	23	10.7	3.1	516
April	40	4.3	1.5	250
May	109	0.5	9.9	1 627
June	147	0.3	39.3	6 445
July	154	0.0	65.1	10 673
August	157	0.0	76.1	12 486
September	96	0.0	30.4	4 986
October	49	2.1	8.6	1 407
November	26	10.3	6.3	1 030
December	16	13.0	4.8	790

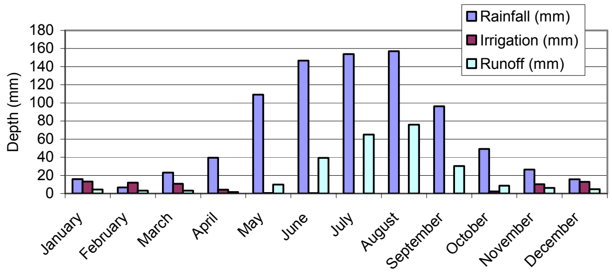
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	845	28.4	224	36 714
1999	1 054	77.8	464	76 077
2000	903	77.1	328	53 717
2001	640	82.3	135	22 163
2002	797	72.8	220	36 056
2003	782	62.8	146	23 891
2004	792	76.3	245	40 119
2005	1 012	52.2	321	52 717
2006	603	71.8	129	21 085
2007	967	61.6	319	52 317
Average	840	66.3	253	41 486









Nash-Sutcliffe Efficiency: *E*	na	
Obs. avg. annual runoff (mm)	na	
Mod. avg. annual runoff (mm)	253	
Difference:	na	
Summer RMSE	na	
Winter RMSE:	na	
Mean summer runoff (Nov-Apr) (mm)	24	**Modelled data**
Mean summer discharge (Nov-Apr) (ML)	3,860	
Mean winter runoff (May-Oct) (mm)	229	
Mean winter discharge (May-Oct) (ML)	37,626	
Discharge % of inputs (average)	28%	
Discharge % of inputs (dry 2006)	19%	
Discharge % of inputs (wet 1999)	41%	

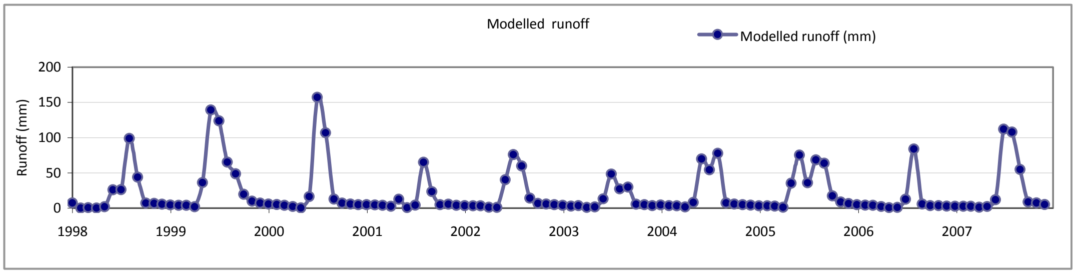


Figure 4.12 Collie Lower 1 – summary statistics

4.7 Upper Preston (611009)

The Upper Preston catchment is located on the Darling Plateau in the headwaters of the Preston River. The catchment is 72 per cent vegetated. Summer irrigation is supplied to the catchment from the PVIC; however, total irrigation inflows generally average less then 1 mm/month across the catchment.

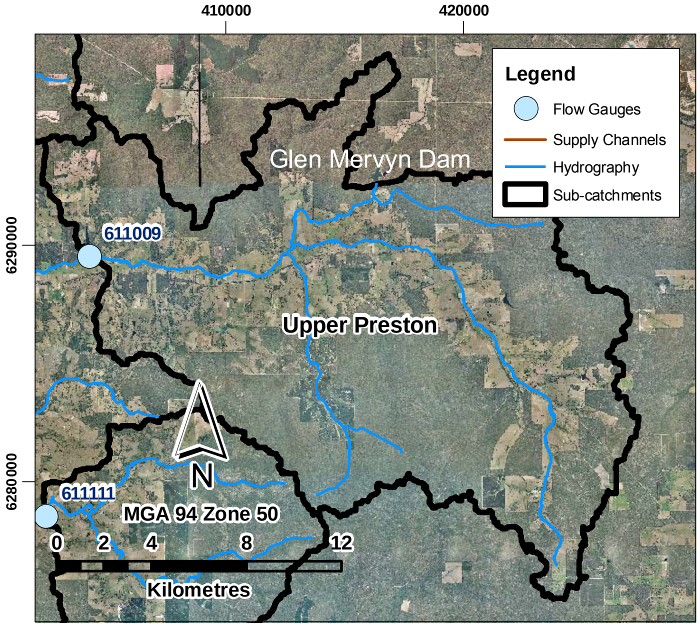


Figure 4.13 Upper Preston catchment

The model calibrated well for the Upper Preston, with a high value of ε = 0.83, although the 10-year total volume of flow was under-predicted by 8 per cent. Summer base-flows and winter peak-flows were accurately modelled.

Despite the summer irrigation, the catchment is relatively dry as a result of the large tracts of uncleared native vegetation. Summer flows generally do not exceed 1 mm/month (but rarely reach zero) and, on average, discharge is only 8 per cent of the total rainfall and irrigation inputs. Summer flow accounts for only 7 per cent of total annual flow.

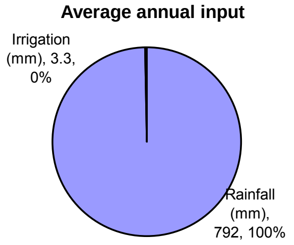
See Figure 4.14 on the following page for full summary statistics.

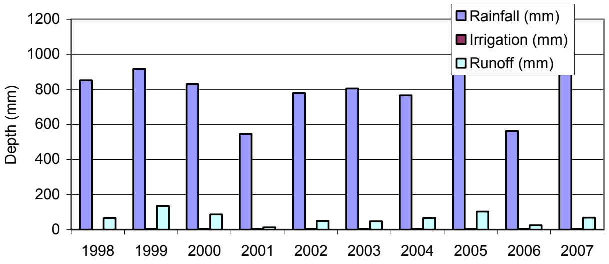
Average monthly statistics (modelled)

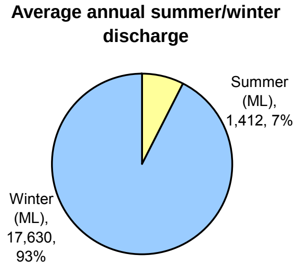
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	14	0.8	0.7	192
February	6	0.9	0.5	154
March	23	0.7	0.5	138
April	40	0.5	0.4	130
May	103	0.0	2.9	824
June	127	0.0	7.1	2 044
July	141	0.0	12.8	3 702
August	150	0.0	21.8	6 296
September	98	0.0	12.8	3 699
October	51	0.0	3.7	1 066
November	25	0.0	1.7	498
December	16	0.5	1.0	300

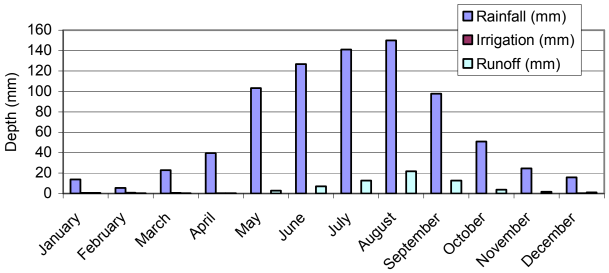
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	853	0.4	66	18 991
1999	917	3.3	134	38 660
2000	831	3.7	87	25 090
2001	546	3.9	12	3 539
2002	780	3.2	49	14 292
2003	806	3.3	47	13 723
2004	766	4.0	67	19 391
2005	967	3.1	103	29 878
2006	562	3.5	24	6 993
2007	897	4.2	69	19 861
Average	792	3.3	66	19 042

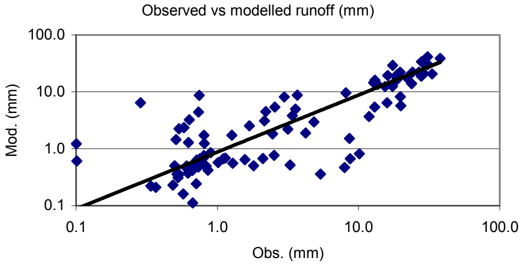








Nash-Sutcliffe Efficiency: ***E***	0.83	
Obs. avg. annual runoff (mm)	74	
Mod. avg. annual runoff (mm)	66	
Difference:	-8.34%	
Summer RMSE	1.35	
Winter RMSE:	4.99	
Mean summer runoff (Nov-Apr) (mm)	5	**Modelled data**
Mean summer discharge (Nov-Apr) (ML)	1,412	
Mean winter runoff (May-Oct) (mm)	61	
Mean winter discharge (May-Oct) (ML)	17,630	
Discharge % of inputs (average)	8%	
Discharge % of inputs (dry 2006)	4%	
Discharge % of inputs (wet 1999)	15%	



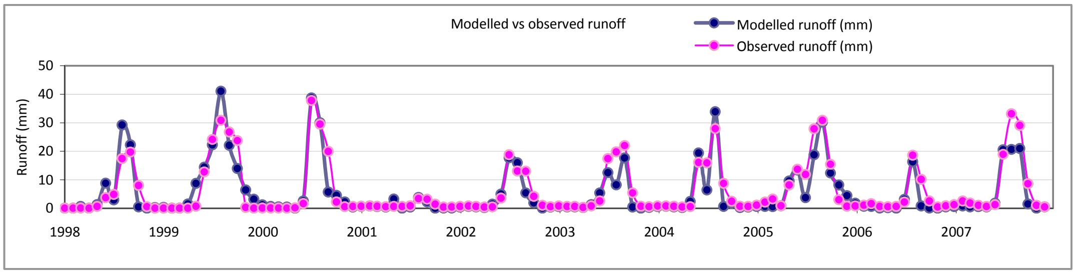


Figure 4.14 Upper Preston – calibration results and summary statistics

4.8 Thomson Brook (611111)

The Thomson Brook catchment is located on the Darling Plateau, immediately south of the Upper Preston, and is 74 per cent vegetated. The catchment's hydrology is dominated by winter flows, which make up 97 per cent of total annual flows. During the summer months, the upper reaches of the Thomson Brook dry completely, with no measured flow between December and April in most years. The absence of summer flows is explained by very low amounts of groundwater discharge, as deep-rooted vegetation uses groundwater before it is at a height where stream intersection occurs. In a dry year, discharge is only 5 per cent of rainfall.

The model calibrated well from 2001 onwards; however, there were some inconsistencies between observed and modelled data before this (see Figure 4.16 on the following page). Modelled 10-year total flows were only 1 per cent more than observed flows, and summer low-flows were well replicated. The Thomson Brook catchment contributes 3 per cent of total flow to the Leschenault Estuary on average.

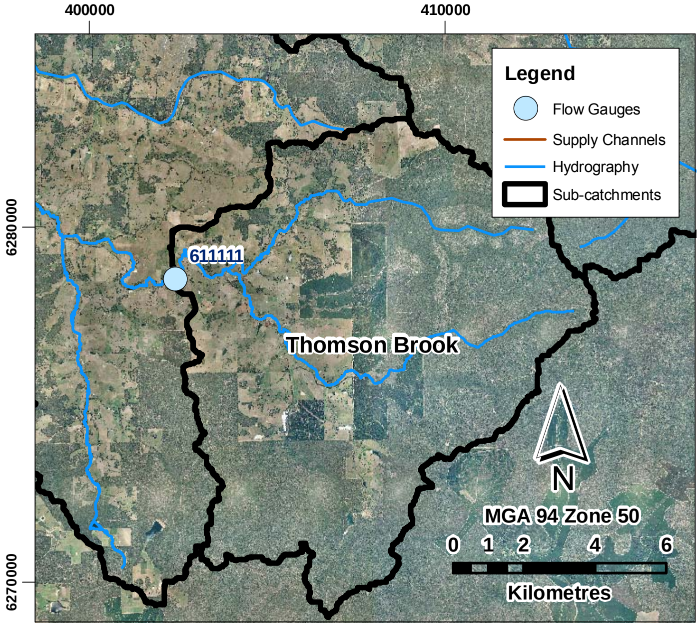


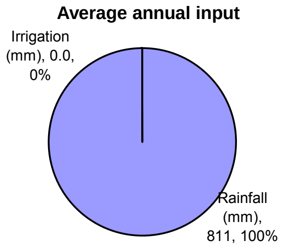
Figure 4.15 Thomson Brook catchment

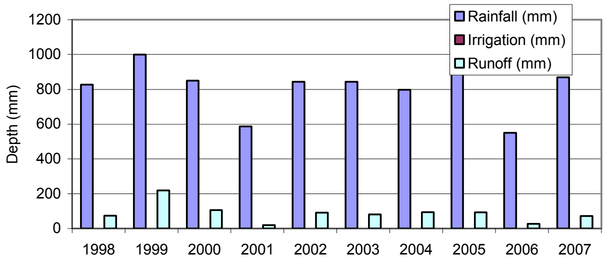
Average monthly statistics (modelled)

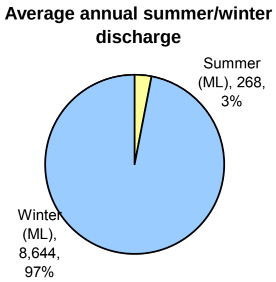
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	13	0.0	0.3	32
February	5	0.0	0.1	14
March	23	0.0	0.2	23
April	42	0.0	0.4	44
May	109	0.0	5.4	549
June	130	0.0	11.3	1 157
July	146	0.0	20.3	2 067
August	150	0.0	28.1	2 869
September	100	0.0	15.7	1 604
October	52	0.0	3.9	398
November	25	0.0	1.0	103
December	18	0.0	0.5	53

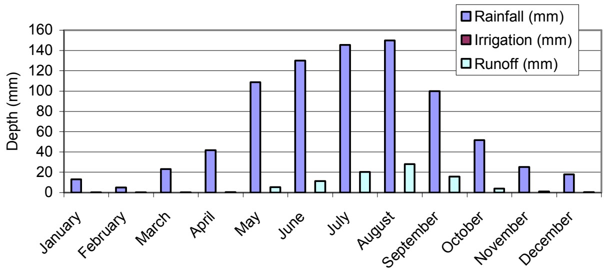
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	826	0.0	73	7 482
1999	1 000	0.0	219	22 330
2000	849	0.0	105	10 716
2001	588	0.0	19	1 916
2002	843	0.0	91	9 300
2003	844	0.0	81	8 220
2004	797	0.0	94	9 635
2005	947	0.0	93	9 483
2006	549	0.0	27	2 711
2007	869	0.0	72	7 332
Average	811	0.0	87	8 912


Average annual input

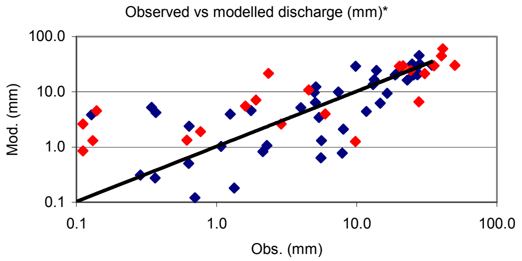


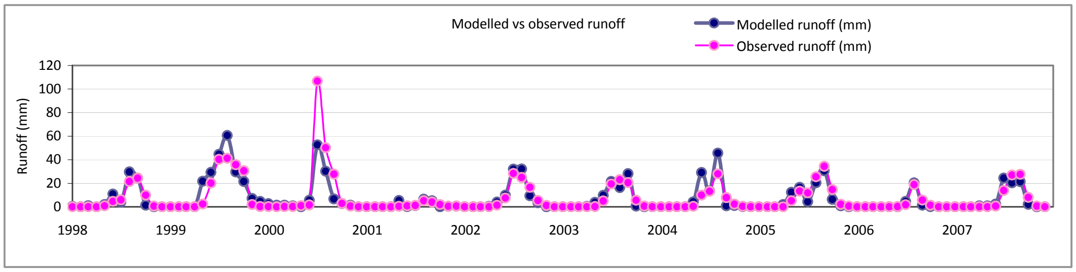

Average annual summer/winter discharge



Nash-Sutcliffe Efficiency: *E*	0.72
Obs. avg. annual runoff (mm)	88
Mod. avg. annual runoff (mm)	87
Difference:	0.24%
Summer RMSE	1.04
Winter RMSE:	10.23
Mean summer runoff (Nov-Apr) (mm)	3
Mean summer discharge (Nov-Apr) (ML)	268
Mean winter runoff (May-Oct) (mm)	85
Mean winter discharge (May-Oct) (ML)	8,644
Discharge % of inputs (average)	11%
Discharge % of inputs (dry 2006)	5%
Discharge % of inputs (wet 1999)	22%

Modelled data


Observed vs modelled discharge (mm)*


Modelled vs observed runoff

**1998-2000 data shown in red*

Figure 4.16 Thomson Brook – calibration results and summary statistics

4.9 Preston – Donnybrook (611006)

This catchment is located on the Darling Plateau immediately above the Donnybrook town site and below the confluence of the Preston River and Thomson Brook. The catchment is partially cleared, with 44 per cent covered by native vegetation.

Upstream observed discharge time-series from 611111 and 611009 were subtracted from the observed flow at Donnybrook before calibration. This introduced uncertainty into the calibration because gauge errors were compounded in the calculations.

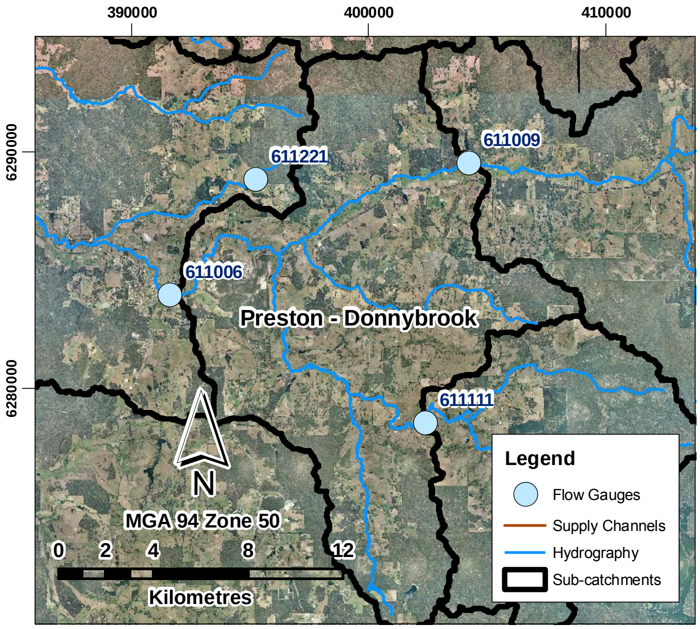


Figure 4.17 Preston – Donnybrook catchment

The Preston–Donnybrook catchment calibrated with a moderately high ε of 0.74, and a difference of -11 per cent between modelled and observed total discharge over the 10-year period modelled. This under-prediction in discharge is related to the winter flows of 2005–07. Low flows in spring and early summer were over-predicted in several years.

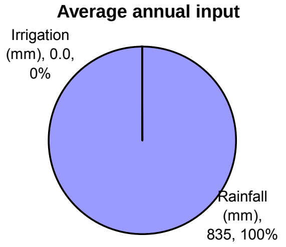
In summer, catchment discharge reduces to zero between December and April in most years, probably due to the presence of deep-rooted vegetation over much of the catchment. The catchment is relatively dry, with discharge only 13 per cent of rainfall in an average year and 95 per cent of flow occurring in winter, as displayed in Figure 4.18.

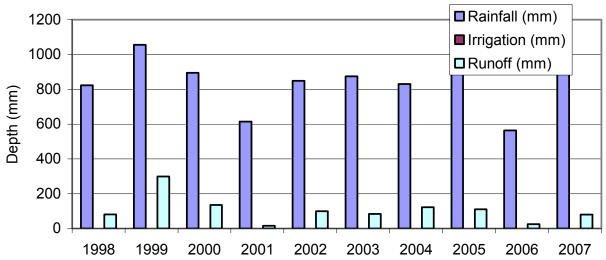
Average monthly statistics (modelled)

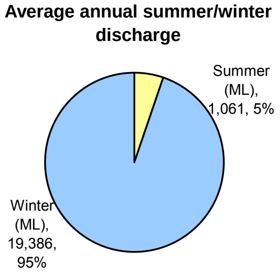
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	13	0.0	1.2	233
February	7	0.0	0.1	18
March	23	0.0	0.1	22
April	41	0.0	0.2	34
May	111	0.0	4.2	825
June	139	0.0	12.6	2 454
July	149	0.0	23.4	4 556
August	154	0.0	34.0	6 623
September	101	0.0	19.1	3 727
October	52	0.0	6.2	1 201
November	25	0.0	2.8	545
December	19	0.0	1.1	208

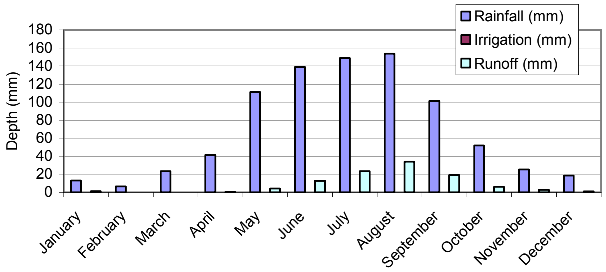
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	822	0.0	81	15 877
1999	1 056	0.0	299	58 224
2000	894	0.0	135	26 346
2001	614	0.0	15	2 900
2002	848	0.0	99	19 252
2003	874	0.0	83	16 272
2004	830	0.0	122	23 815
2005	955	0.0	110	21 475
2006	564	0.0	24	4 671
2007	888	0.0	80	15 639
Average	835	0.0	105	20 447



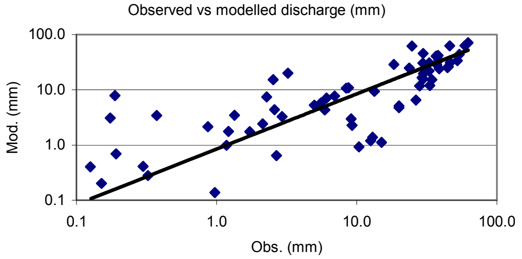






Nash-Sutcliffe Efficiency: *E*	0.74
Obs. avg. annual runoff (mm)	123
Mod. avg. annual runoff (mm)	105
Difference:	-11.59%
Summer RMSE	2.42
Winter RMSE:	10.46
Mean summer runoff (Nov-Apr) (mm)	5
Mean summer discharge (Nov-Apr) (ML)	1,061
Mean winter runoff (May-Oct) (mm)	99
Mean winter discharge (May-Oct) (ML)	19,386
Discharge % of inputs (average)	13%
Discharge % of inputs (dry 2006)	4%
Discharge % of inputs (wet 1999)	28%

Modelled data



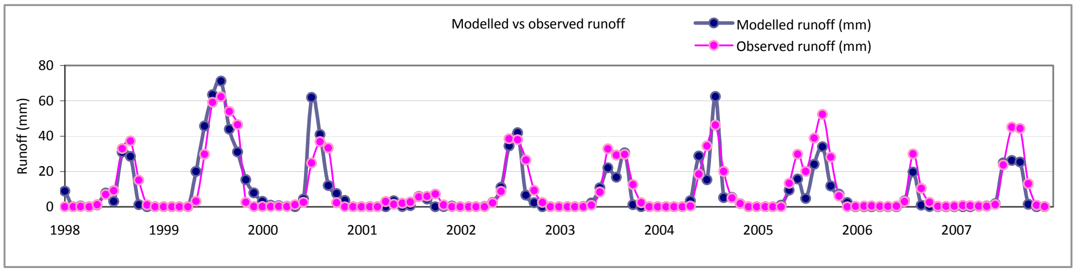


Figure 4.18 Preston – Donnybrook – calibration results and summary statistics

4.10 Mid Preston (611004)

This catchment is located on the Darling Scarp downstream of Donnybrook. The pour point at the catchment's lower end is located on the edge of the Swan coastal plain. The catchment is 64 per cent vegetated.

Observed upstream flows from 611006 were subtracted from the flow time-series at 611004, introducing uncertainty in the observed values. There was a good match between observed and modelled discharge after calibration, which achieved ε of 0.75 and under-predicted flow by 10 per cent over the 10-year period modelled.

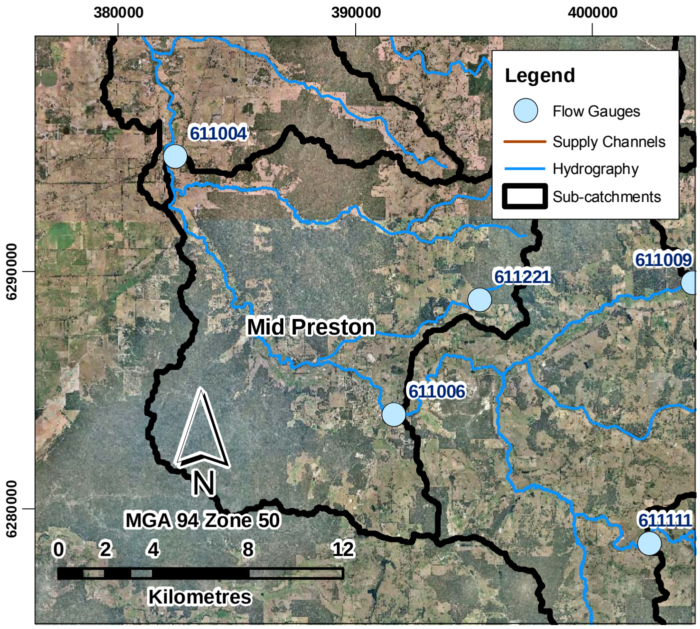


Figure 4.19 Mid Preston catchment

Despite the presence of deep-rooted vegetation, the Mid Preston was relatively wet compared with other vegetated catchments, such as the Upper Preston and Thomson Brook. The catchment was dry compared with the irrigated catchments on the Swan coastal plain and, on average, discharge was only 13 per cent of rainfall.

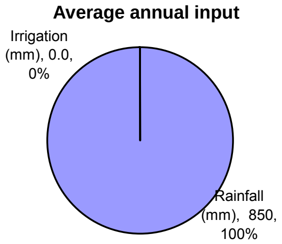
There was summer discharge in most years, but generally this was less than 2 mm/month. See Figure 4.20 on the following page for summary statistics.

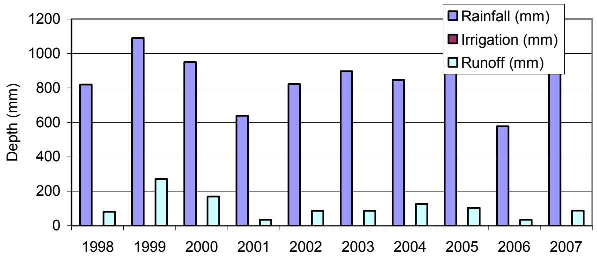
Average monthly statistics (modelled)

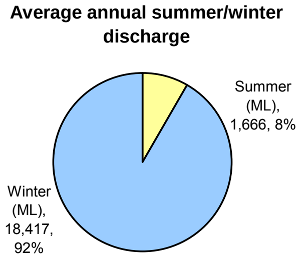
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	14	0.0	1.5	275
February	8	0.0	1.4	262
March	23	0.0	1.4	257
April	41	0.0	1.4	256
May	113	0.0	4.2	780
June	146	0.0	13.3	2 476
July	151	0.0	24.3	4 519
August	158	0.0	36.3	6 747
September	100	0.0	17.2	3 205
October	52	0.0	3.7	691
November	25	0.0	1.8	330
December	20	0.0	1.5	286

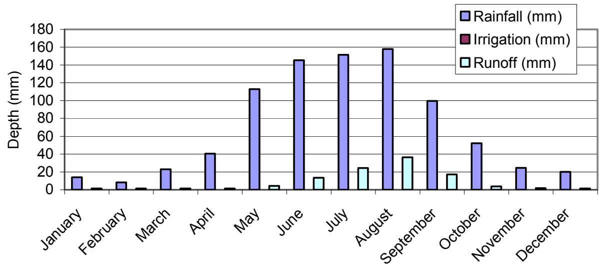
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	820	0.0	82	15 213
1999	1 090	0.0	270	50 272
2000	950	0.0	169	31 483
2001	638	0.0	35	6 529
2002	822	0.0	87	16 158
2003	897	0.0	87	16 147
2004	847	0.0	125	23 337
2005	962	0.0	103	19 116
2006	578	0.0	34	6 381
2007	898	0.0	87	16 185
Average	850	0.0	108	20 082

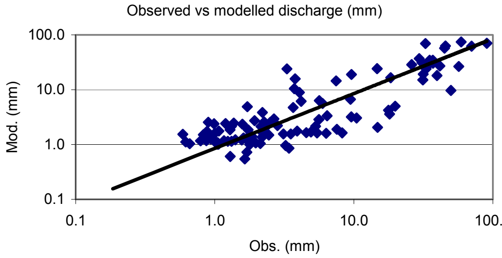








Nash-Sutcliffe Efficiency: ***E***	0.75	
Obs. avg. annual runoff (mm)	120	
Mod. avg. annual runoff (mm)	108	
Difference:	-10.52%	
Summer RMSE	1.32	
Winter RMSE:	11.38	
Mean summer runoff (Nov-Apr) (mm)	9	**Modelled data**
Mean summer discharge (Nov-Apr) (ML)	1,666	
Mean winter runoff (May-Oct) (mm)	99	
Mean winter discharge (May-Oct) (ML)	18,417	
Discharge % of inputs (average)	13%	
Discharge % of inputs (dry 2006)	6%	
Discharge % of inputs (wet 1999)	25%	



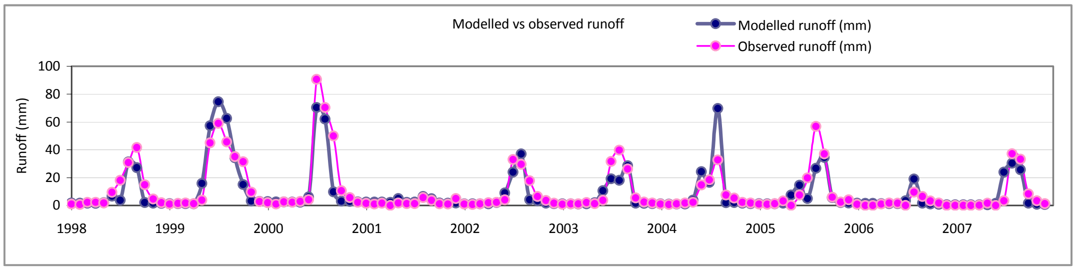


Figure 4.20 Mid Preston – calibration results and summary statistics

4.11 Upper Ferguson – 611017

This catchment is located in the upper reaches of the Ferguson River and includes areas of the Darling Scarp and Swan coastal plain. The catchment is 62 per cent vegetated and is very dry during summer, with almost zero flow between November and April in most years. Summer flow totals only 4 per cent of annual flows.

Calibration resulted in a high ε of 0.83, with the 10-year total modelled flow 7 per cent less than the observed flow. Both winter and summer flows calibrated well (see Figure 4.22).

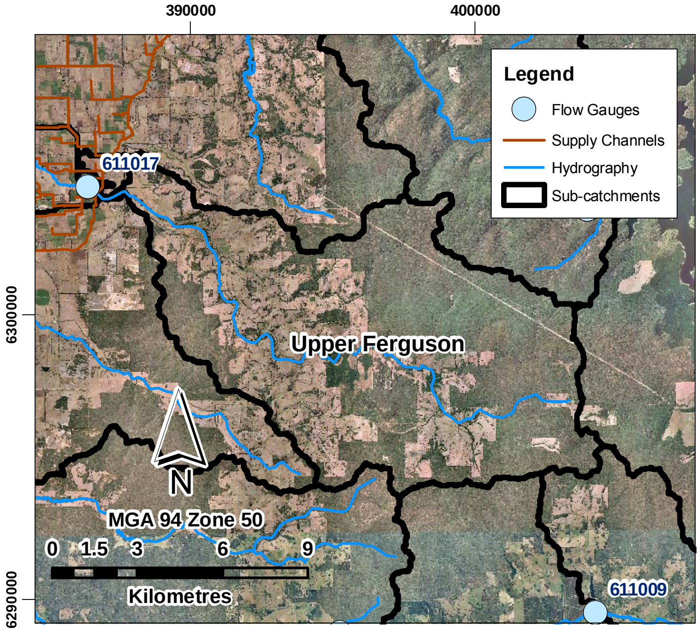


Figure 4.21 Upper Ferguson catchment

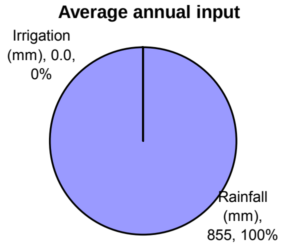
The Upper Ferguson is one of the driest catchments in the Leschenault. It contributed only 4 per cent of total flow to the estuary for the period 1998 to 2007.

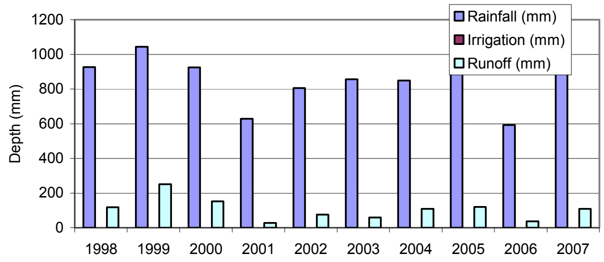
Average monthly statistics (modelled)

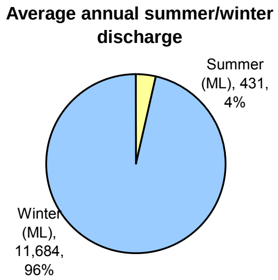
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	14	0.0	0.2	17
February	8	0.0	0.0	4
March	24	0.0	0.2	20
April	42	0.0	0.4	43
May	111	0.0	5.7	647
June	147	0.0	15.6	1 783
July	153	0.0	23.2	2 640
August	159	0.0	33.8	3 851
September	101	0.0	18.4	2 093
October	51	0.0	5.9	668
November	27	0.0	2.4	279
December	18	0.0	0.6	68

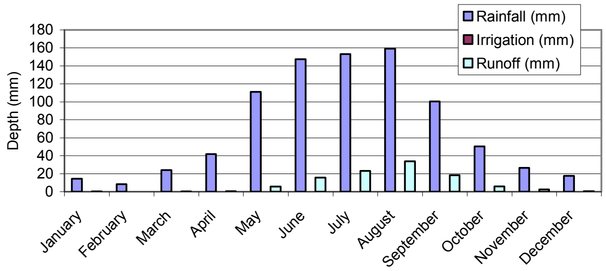
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	927	0.0	119	13 526
1999	1 045	0.0	252	28 714
2000	926	0.0	152	17 367
2001	629	0.0	28	3 216
2002	806	0.0	76	8 663
2003	857	0.0	59	6 744
2004	849	0.0	110	12 558
2005	980	0.0	120	13 694
2006	592	0.0	37	4 204
2007	935	0.0	109	12 464
Average	855	0.0	106	12 115

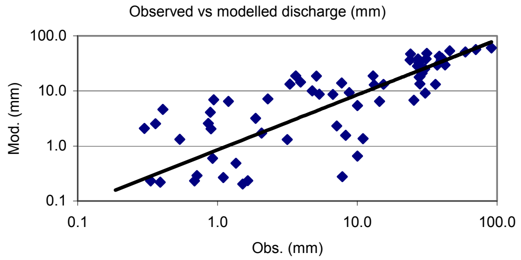








Nash-Sutcliffe Efficiency: E	0.83	
Obs. avg. annual runoff (mm)	112	
Mod. avg. annual runoff (mm)	106	
Difference:	-6.96%	
Summer RMSE	1.58	
Winter RMSE:	9.64	
Mean summer runoff (Nov-Apr) (mm)	4	**Modelled data**
Mean summer discharge (Nov-Apr) (ML)	431	
Mean winter runoff (May-Oct) (mm)	102	
Mean winter discharge (May-Oct) (ML)	11,684	
Discharge % of inputs (average)	12%	
Discharge % of inputs (dry 2006)	6%	
Discharge % of inputs (wet 1999)	24%	



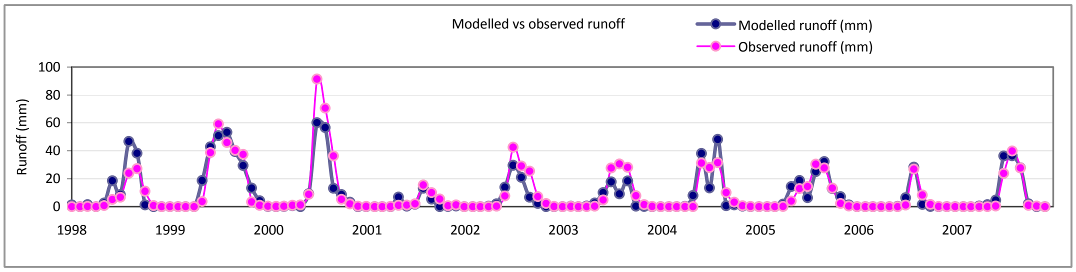


Figure 4.22 Upper Ferguson – calibration results and summary statistics

4.12 Lower Ferguson (611007)

The Lower Ferguson catchment is located on the Swan coastal plain, with the pour point just above the Preston–Ferguson confluence. It is 93 per cent cleared of native vegetation. The catchment has a high density of irrigation supply points for horticulture, and receives a large volume of irrigation water for its size (2489 ML). This is equivalent to 108 mm additional depth in rainfall as a result of irrigation, which makes the Lower Ferguson the most heavily irrigated catchment in the Leschenault for its size.

The gauge associated with this catchment (611007) was inaccurate and could not be used for calibration. Thus the parameter sets for the Lower Collie and Wellesley catchments were used to model discharge in the Lower Ferguson.

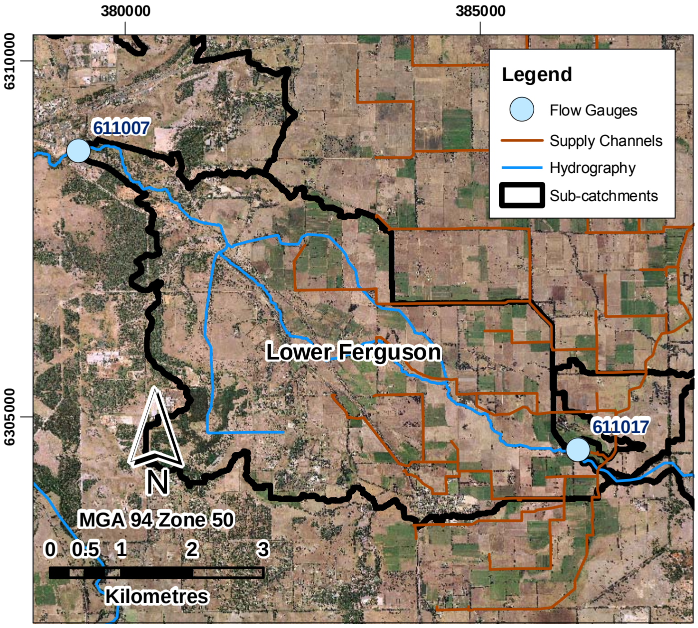


Figure 4.23 Lower Ferguson catchment

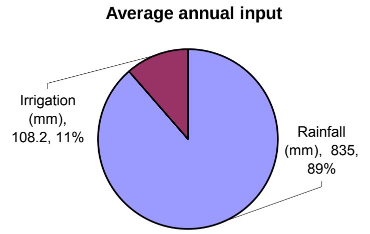
This catchment is one of the wettest in the area. Discharge is 28 per cent of the combined rainfall and irrigation in an average year. This figure increases to 43 per cent in a very wet year, and is still 17 per cent in a dry year. These high discharge values are probably the result of heavy irrigation and catchment clearing. The Lower Ferguson is the smallest catchment delineated (23 km^2) and therefore contributes to only 2 per cent of total flows reaching the estuary. See Figure 4.24 overleaf for summary statistics.

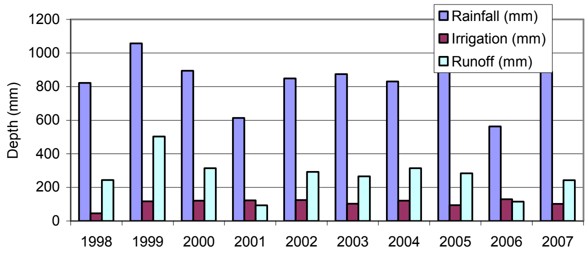
Average monthly statistics (modelled)

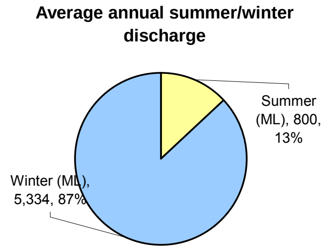
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	13	22.2	6.8	156
February	7	20.0	5.6	128
March	23	17.7	5.1	116
April	41	5.9	2.1	49
May	111	0.2	11.1	255
June	139	0.2	39.9	918
July	149	0.0	64.4	1 482
August	154	0.0	73.0	1 679
September	101	0.0	34.2	786
October	52	2.3	9.3	214
November	25	17.6	8.3	190
December	19	22.0	7.0	161

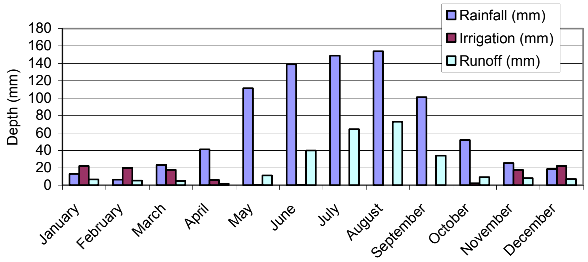
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	822	45.7	244	5 604
1999	1 056	117.0	503	11 572
2000	894	121.6	314	7 232
2001	614	122.7	92	2 124
2002	848	124.8	292	6 717
2003	874	103.4	266	6 115
2004	830	121.2	314	7 233
2005	955	93.9	283	6 520
2006	564	129.5	115	2 646
2007	888	102.2	242	5 575
Average	835	108.2	267	6 134









Nash-Sutcliffe Efficiency: E	na	
Obs. avg. annual runoff (mm)	na	
Mod. avg. annual runoff (mm)	267	
Difference:	na	
Summer RMSE	na	
Winter RMSE:	na	
Mean summer runoff (Nov-Apr) (mm)	35	**Modelled data**
Mean summer discharge (Nov-Apr) (ML)	800	
Mean winter runoff (May-Oct) (mm)	232	
Mean winter discharge (May-Oct) (ML)	5,334	
Discharge % of inputs (average)	28%	
Discharge % of inputs (dry 2006)	17%	
Discharge % of inputs (wet 1999)	43%	

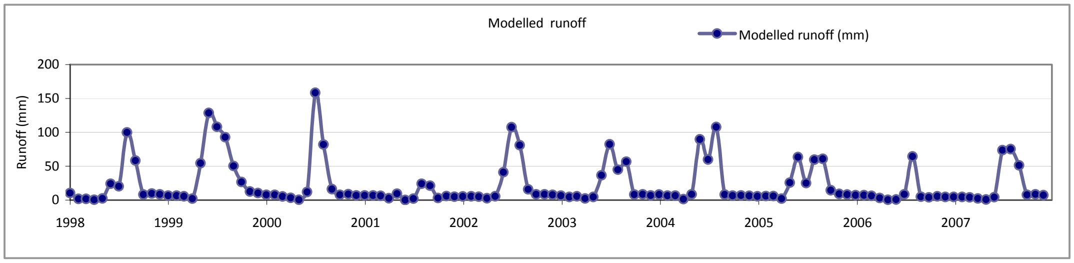


Figure 4.24 Lower Ferguson – summary statistics

4.13 Lower Preston (611010)

The Lower Preston catchment is located on the Swan coastal plain downstream of the Lower Ferguson and Mid Preston catchments. In an average year it receives a negligible amount of summer irrigation, amounting to only 1 per cent of combined rainfall and irrigation. The catchment includes some vegetated areas around a tributary in the Darling Scarp, totalling 27 per cent of the catchment area.

The gauge at the pour point of the Preston River (611010) was tidally influenced and could not be used for calibration. As a result, the parameter set from the Wellesley catchment was used to model discharge for the Lower Preston.

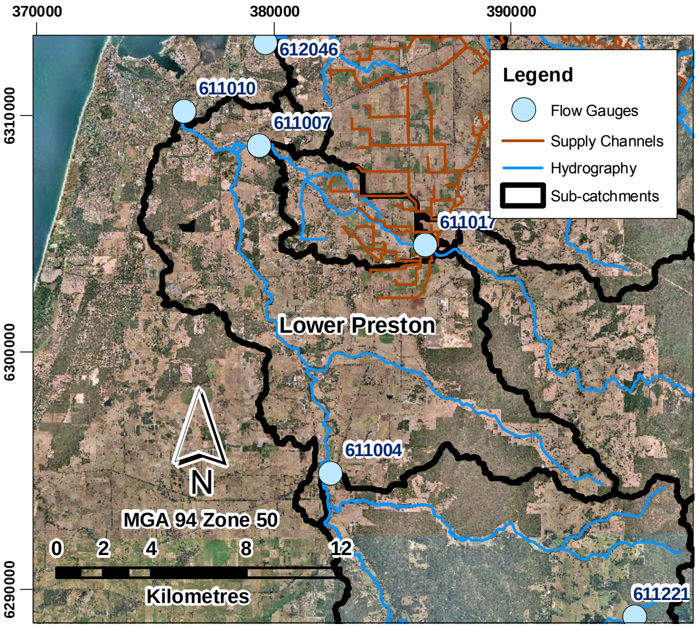


Figure 4.25 Lower Preston catchment

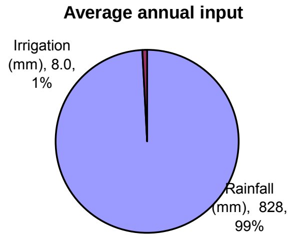
The Lower Preston catchment was slightly wetter than the vegetated catchments in the Upper Preston, but was slightly drier than the other cleared catchments on the Swan coastal plain. Summer flow is about 5 per cent of average annual flow. In a dry year (e.g. 2006) discharge is equal to 19 per cent of total irrigation and rainfall; this increases to 45 per cent in a very wet year (e.g. 1999).

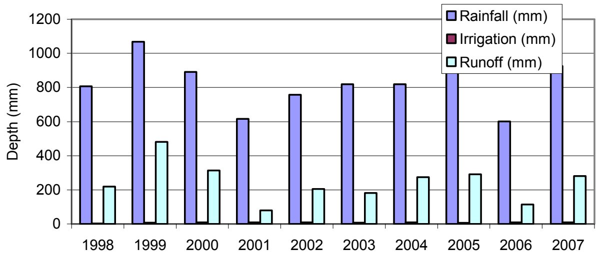
Average monthly statistics (modelled)

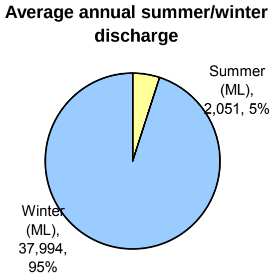
Month	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
January	14	1.7	2.7	435
February	8	1.5	1.3	218
March	22	1.3	1.0	170
April	40	0.3	0.6	106
May	110	0.0	11.0	1 801
June	149	0.0	43.7	7 174
July	150	0.0	65.5	10 749
August	153	0.0	74.2	12 169
September	93	0.0	29.4	4 828
October	47	0.2	7.8	1 273
November	24	1.3	4.2	687
December	19	1.7	2.7	436

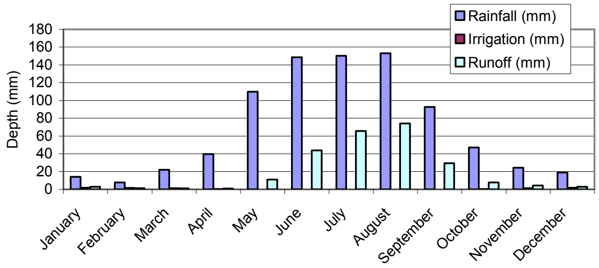
Yearly totals (modelled)

Year	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Discharge (ML)
1998	807	3.1	220	36 039
1999	1 067	8.3	480	78 797
2000	890	9.2	314	51 470
2001	616	8.7	80	13 044
2002	756	9.1	204	33 511
2003	818	8.2	182	29 777
2004	818	9.5	275	45 095
2005	980	6.6	292	47 837
2006	601	9.4	115	18 840
2007	925	8.4	281	46 035
Average	828	8.0	244	40 044









Nash-Sutcliffe Efficiency: E	na	
Obs. avg. annual runoff (mm)	na	
Mod. avg. annual runoff (mm)	244	
Difference:	na	
Summer RMSE	na	
Winter RMSE:	na	
Mean summer runoff (Nov-Apr) (mm)	13	**Modelled data**
Mean summer discharge (Nov-Apr) (ML)	2,051	
Mean winter runoff (May-Oct) (mm)	232	
Mean winter discharge (May-Oct) (ML)	37,994	
Discharge % of inputs (average)	29%	
Discharge % of inputs (dry 2006)	19%	
Discharge % of inputs (wet 1999)	45%	

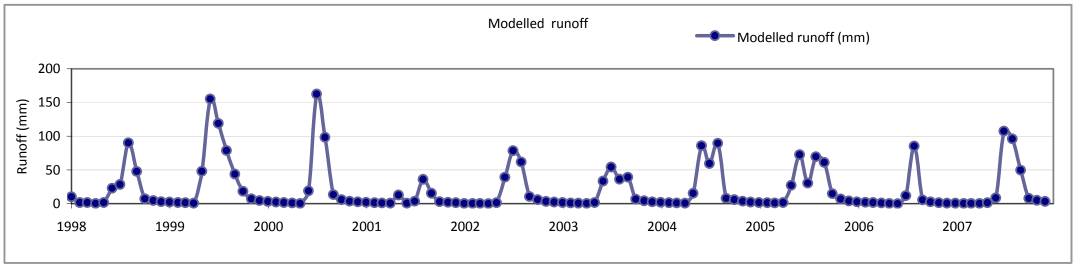


Figure 4.26 Lower Preston – calibration results and summary statistics

5. Model results – Leschenault catchment overview

The Preston, Brunswick and Collie river systems, as well as vegetated versus cleared catchments, have significant differences in their hydrology. These are highlighted in the following section by comparing subcatchments within the Leschenault catchment area. Catchment inputs and summary discharge information is listed in Appendix B.

5.1 Vegetation, rainfall and runoff

The presence of native vegetation in a catchment has a significant effect on its water balance. The density of vegetation, rooting depth, and proportion of vegetated area within a given catchment is correlated with evapotranspiration and consequently catchment discharge. Figure 5.1 demonstrates that with increased vegetation, runoff is reduced. The noticeable outlier in the graph below is associated with the Brunswick Upper 2 catchment, which consistently has higher flows than other vegetated catchments. It has been suggested that the Brunswick has a number of gaining reaches intersecting groundwater (Annan 2006) and is subject to higher levels of groundwater discharge and summer base-flow than the other catchments. When Brunswick Upper 2 was removed from the analysis below, the correlation coefficient (R^2) increased to 0.91 (see inset graph below), indicating a strong relationship between catchment clearing and average annual discharge.

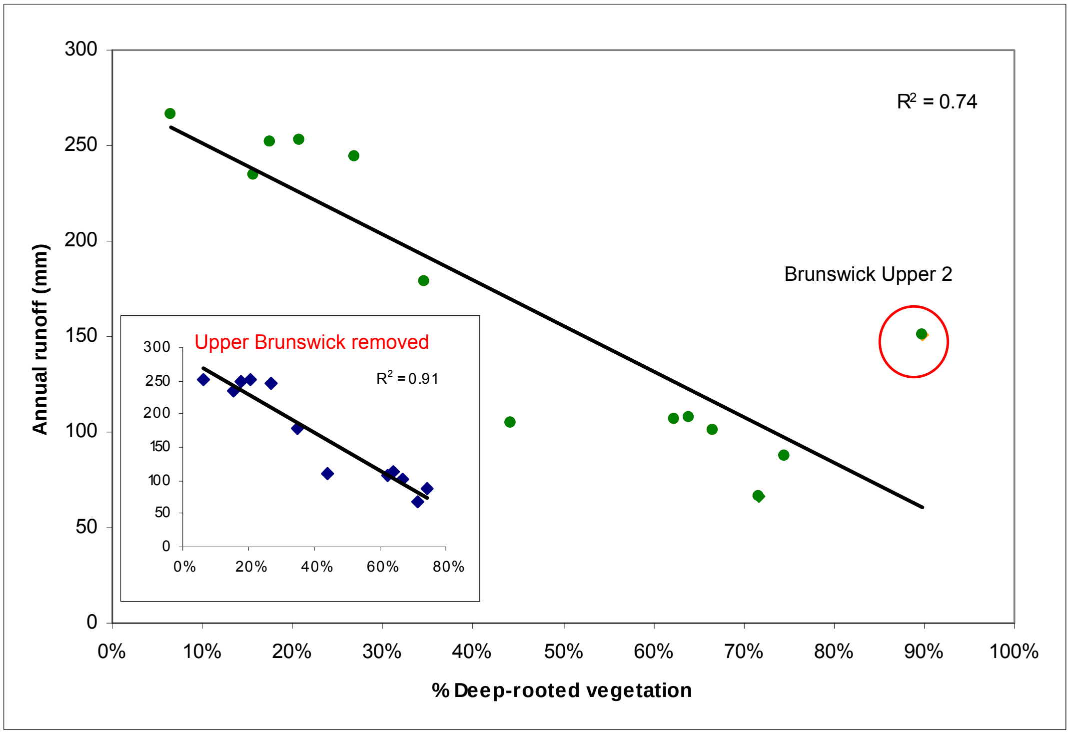


Figure 5.1 Percentage deep-rooted vegetation in relation to mean annual runoff

5.2 Affects of reduced rainfall on discharge

Although climate scenario modelling was not conducted, the effects of reduced rainfall on discharge can be modelled by fitting modelled total annual discharge and rainfall to a hyperbolic tangent function (after Boughton 1966). Figure 5.2 illustrates the difference in annual timestep rainfall-runoff relationships for the Wellesley and Thomson Brook catchments. As the catchments dry, discharge reduces disproportionately to decreases in rainfall. For example, in the Wellesley, yearly rainfall of 1000 mm results in around 230 mm discharge, while rainfall of 800 mm results in a decrease to 130 mm discharge. A 20 per cent reduction in rainfall results in a 43 per cent reduction in discharge. These figures are approximate only, and stochastic climate modelling is required to better predict the influence of climate change on catchment behaviour. The total discharge to the estuary is likely to decrease dramatically under reduced rainfall.

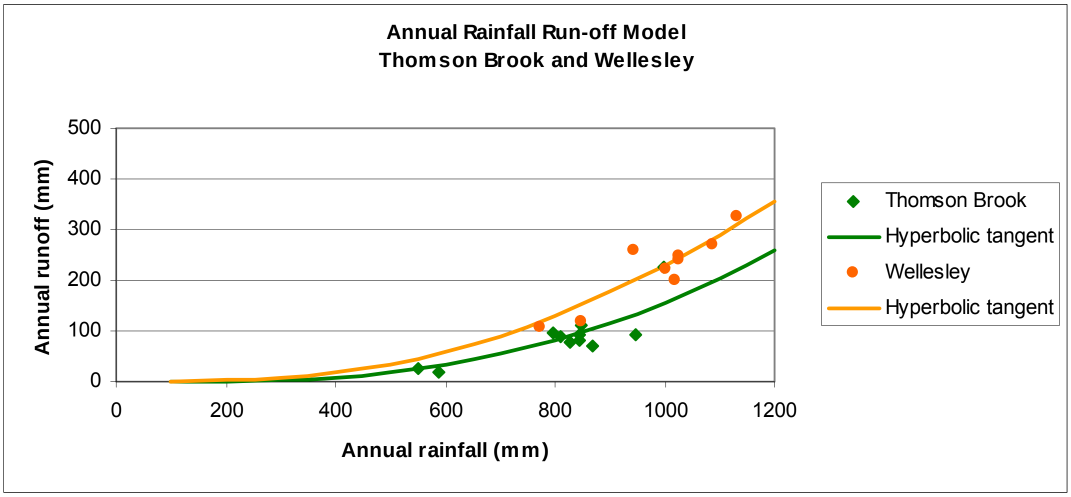


Figure 5.2 Annual rainfall-runoff for Wellesley and Thomson Brook

As rainfall increased in the cleared Wellesley catchment, runoff increased more dramatically. This is because crops and grasses with shallow root systems are less able to transpire large volumes of water than native forests and shrub land. As rainfall decreases, the catchments function in a similar fashion – evapotranspiring the majority of available water. As rainfall is reduced, the relative contribution of discharge from uncleared catchments to the Leschenault Estuary will decrease, as shown in Figure 5.3.

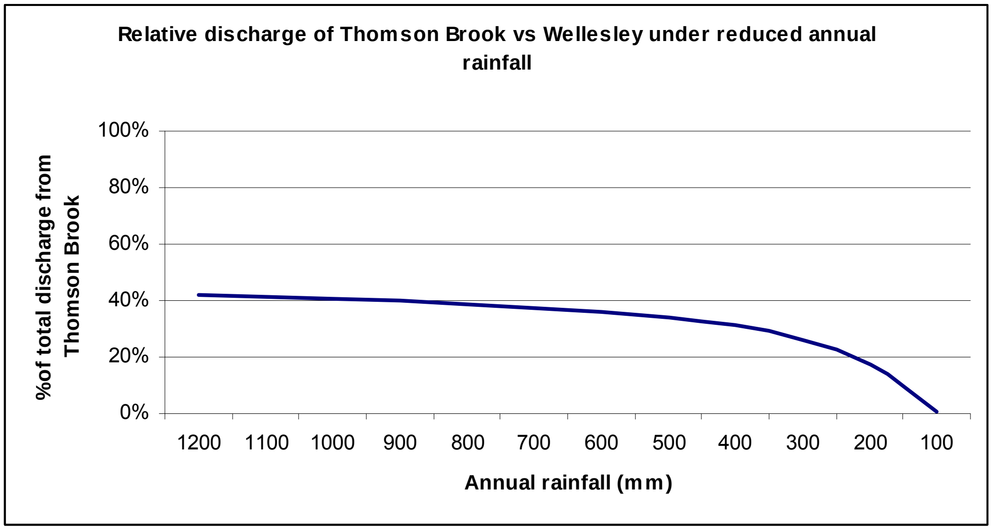


Figure 5.3 Relative discharge of Thomson Brook versus Wellesley under reduced rainfall

It is possible to speculate about possible climate scenarios, although these have not been modelled specifically as part of this project. However, all catchments experienced a disproportionate reduction in runoff as rainfall decreased. This has the potential to decrease total nutrient loads, but possibly increase nutrient concentration in a drying climate. Reduced runoff in dry years will increase competition for water between environmental flows and irrigation requirements.

5.3 Annual irrigation summary

Observed irrigation data was applied to each subcatchment. Irrigation depth (mm) and total volume (ML) were calculated. See Figure 5.4 below.

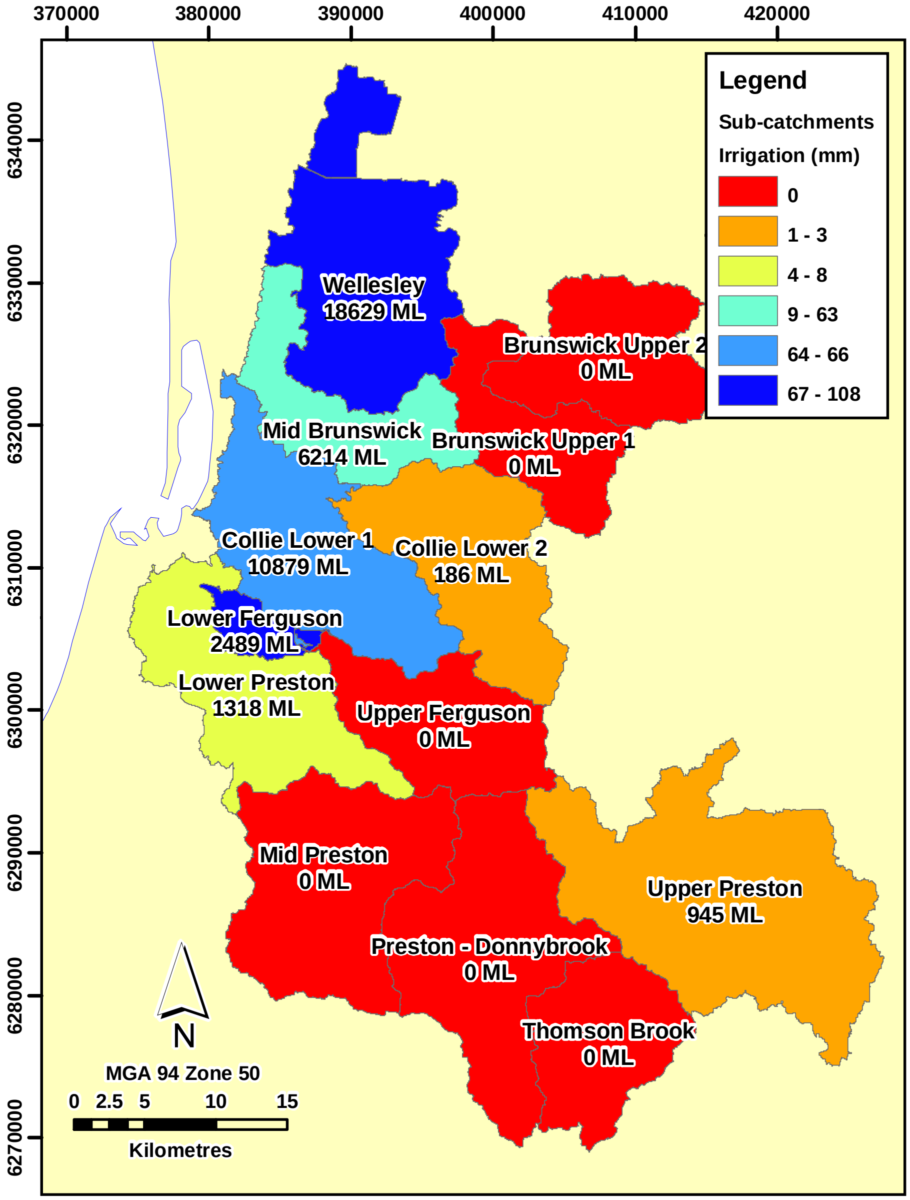


Figure 5.4 Irrigation in the Leschenault catchment

Red areas in the map above indicate catchments that receive very little or no irrigation, relative to their catchment area. The most heavily irrigated catchment is the Wellesley, which is also relatively wet for its size. The Lower Ferguson receives the most irrigation for its size. Irrigation inflows into the coastal plain catchments constitute 90 per cent of the total irrigation supplied by Harvey Water and PVIC for the Leschenault catchment. Irrigation supplied to the Wellesley and Lower Brunswick catchments is sourced primarily from the Harvey Irrigation District. The Collie, Lower Ferguson and Lower Preston catchments receive water from the Collie Irrigation District, and the Upper Preston from the Glen Mervyn Dam.

5.4 Irrigation return flows summary

Average annual irrigation return flows modelled with the irrigation module are shown in Figure 5.5. In irrigated catchments on the Coastal Plain, less than 10 per cent of the annual water-balance is due to irrigation returns. For example the Wellesley has an average annual discharge which totals 50 212 ML, and 3911 ML (8 per cent) of this is irrigation return flow. A similar proportion of annual flow is attributable to irrigation return flow in the Mid Brunswick (9 per cent), Lower Collie (6 per cent), and Lower Ferguson (9 per cent). Irrigation return flow averages around 25 per cent of irrigation water applied, the remaining 75 per cent is assumed to evapo-transpire, with a negligible amount contributing to groundwater recharge.

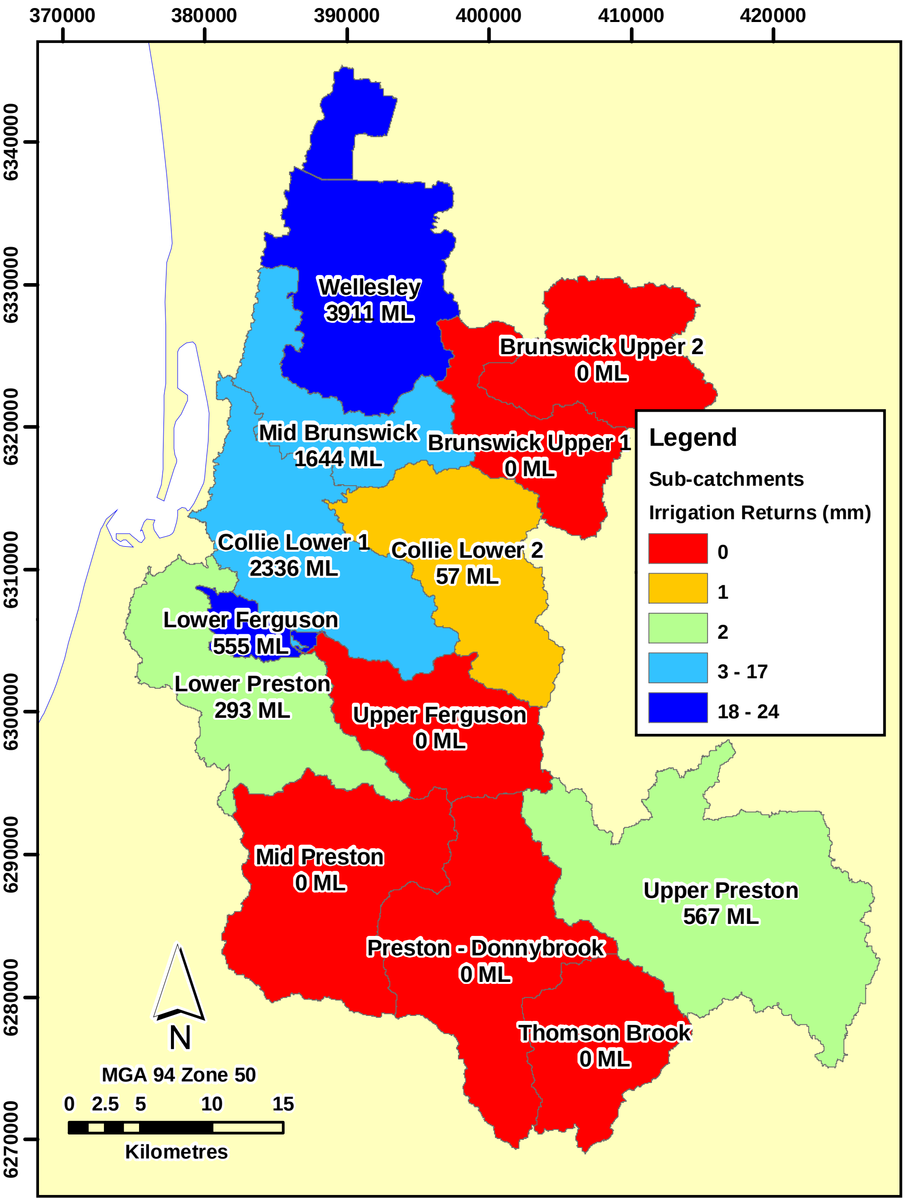


Figure 5.5 *Irrigation return flows in the Leschenault catchment*

5.5 Annual discharge summary

For each catchment, the modelled average annual runoff (mm) was calculated. These are shown in Figure 5.7, with percentage contribution to the total volume of water reaching the Leschenault catchment. The wettest catchments were the cleared, irrigated catchments on the Swan coastal plain. The Brunswick, Collie and Wellesley river systems were considerably wetter than the Preston and Ferguson (upper).

The Preston River and Ferguson (Upper) river systems are dry relative to catchment size as shown in Figure 5.6. Water yield in these catchments averages 122 mm, compared with 244 mm for the Collie and 144 mm for the Brunswick. Several factors contribute to the Preston catchment's lower yield: much of it is located inland of the Darling Scarp and is subject to slightly lower rainfall (see

Figure 5.6); it is more heavily vegetated (56 versus 37 per cent for the Collie and Brunswick); and it receives 6 per cent the volume of irrigation supplied to the Collie, Lower Ferguson and Brunswick catchments.

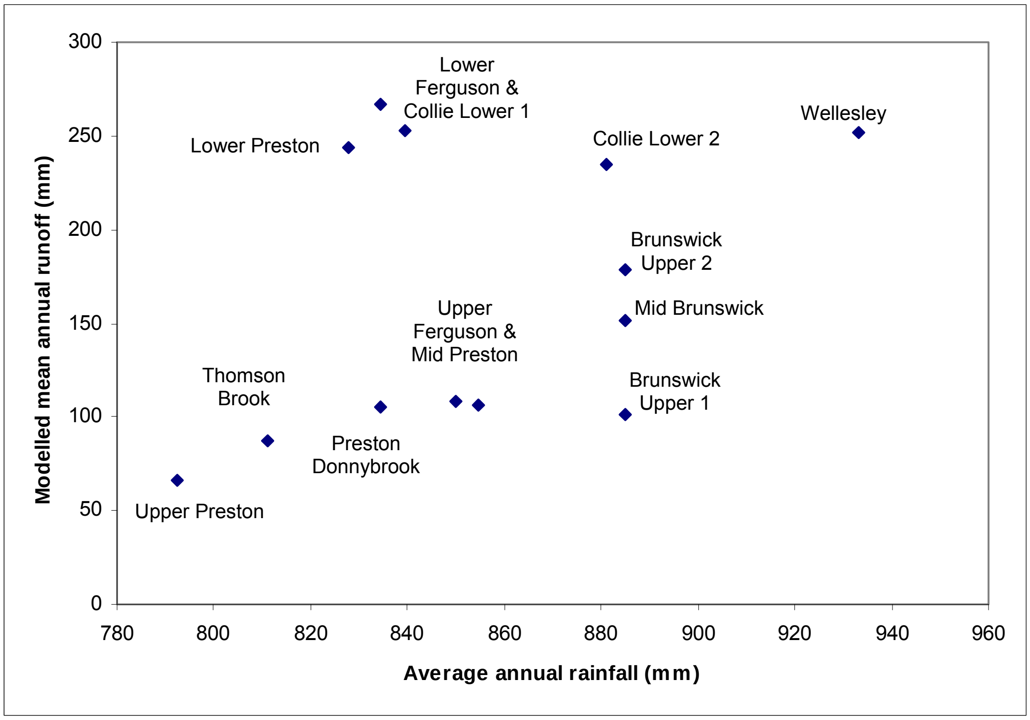


Figure 5.6 Average annual rainfall versus catchment yield

As noted earlier, the upper Brunswick River probably receives additional groundwater discharge, and may intersect a groundwater aquifer. This is evident in the consistently high water yield even in the 90-per-cent-vegetated Brunswick Upper 2 catchment. The catchments generating the most discharge are the Wellesley, Collie Lower 1 and Lower Preston catchments. These catchments receive irrigation water, have high rainfall and are mostly cleared.

In winter, 81 per cent of total discharge to the Leschenault Estuary is sourced from the Brunswick and Preston rivers (40 and 41 per cent respectively), with the remainder from the Lower Collie (19 per cent). In summer (December–February) the proportion of flow from the Brunswick and Collie increases to 72 per cent from 59 per cent in winter, as a result of irrigation return flows. Statistics for winter and summer flows are shown in the Figure 5.8.

The proportion of summer flow (54 per cent, December–February) contributed by irrigated catchments is higher than in winter (41 per cent, June–August). Assuming that irrigation water from cleared catchments is more likely to contain high nutrient concentrations, this indicates that in summer the diluting effect of relatively unpolluted water from forested catchments is reduced, potentially increasing the overall concentration of nutrients in water reaching the Leschenault Estuary. The largest single contributor to total summer flows was the Wellesley catchment, which discharges 5.8 GL of water, or 24 per cent of Leschenault Estuary inflows from December to February inclusive (see Figure 5.9).

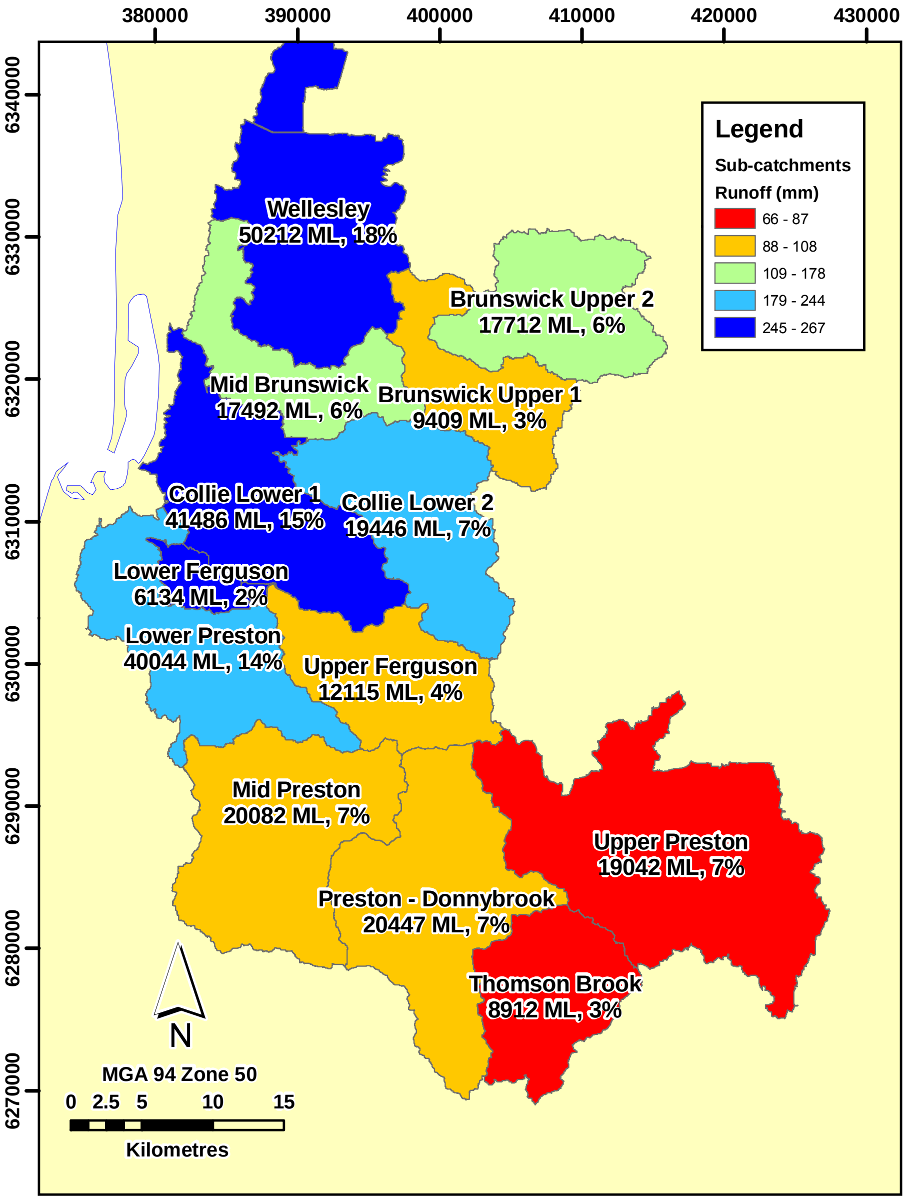


Figure 5.7 Runoff and discharge in the Leschenault catchment

Vegetated catchments	**(GL)**
Total irrigation	1
Total winter flow	56
Total summer flow	3
Total annual flow	87

Vegetated catchments < 50% cleared. Inludes Brunswick Upper 1 & 2, Upper Ferguson, Thomson, Upper Preston, Mid Preston.

Cleared catchments	**(GL)**
Total irrigation	40
Winter flow	133
Summer flow	10
Total annual flow	195

Cleared catchments > 50% cleared. Includes Mid Brunswick, Collie Lower 1 & 2, Lower Ferguson, Preston Donnybrook, Lower Preston, Wellesley.

Non-irrigated catchments	**(GL)**
Total irrigation	2
Winter flow	111
Summer flow	6
Total annual flow	167

Non-irrigated < 10mm annually. Includes Brunswick Upper 1 & 2, Upper Ferguson, Thomson, Upper Preston, Mid Preston, Collie Lower 2, Preston Donnybrook, Lower Preston.

Irrigated catchments	**(GL)**
Total irrigation	38
Winter flow	78
Summer flow	7
Total annual flow	115

Non-irrigated > 10mm annually. Includes Mid Brunswick, Collie Lower 1, Lower Ferguson, Wellesley.

Collie summary	**(GL)**
Winter flow	41
Summer flow	3
Total irrigation	11
Total annual flow	61

Includes Collie Lower catchments

Preston summary	**(GL)**
Winter flow	88
Summer flow	4
Total irrigation	5
Total annual flow	127

Includes Thomson & Ferguson catchments

Brunswick summary	**(GL)**
Winter flow	60
Summer flow	6
Total irrigation	25
Total annual flow	95

Includes Wellesley, Upper and Lower Brunswick catchments

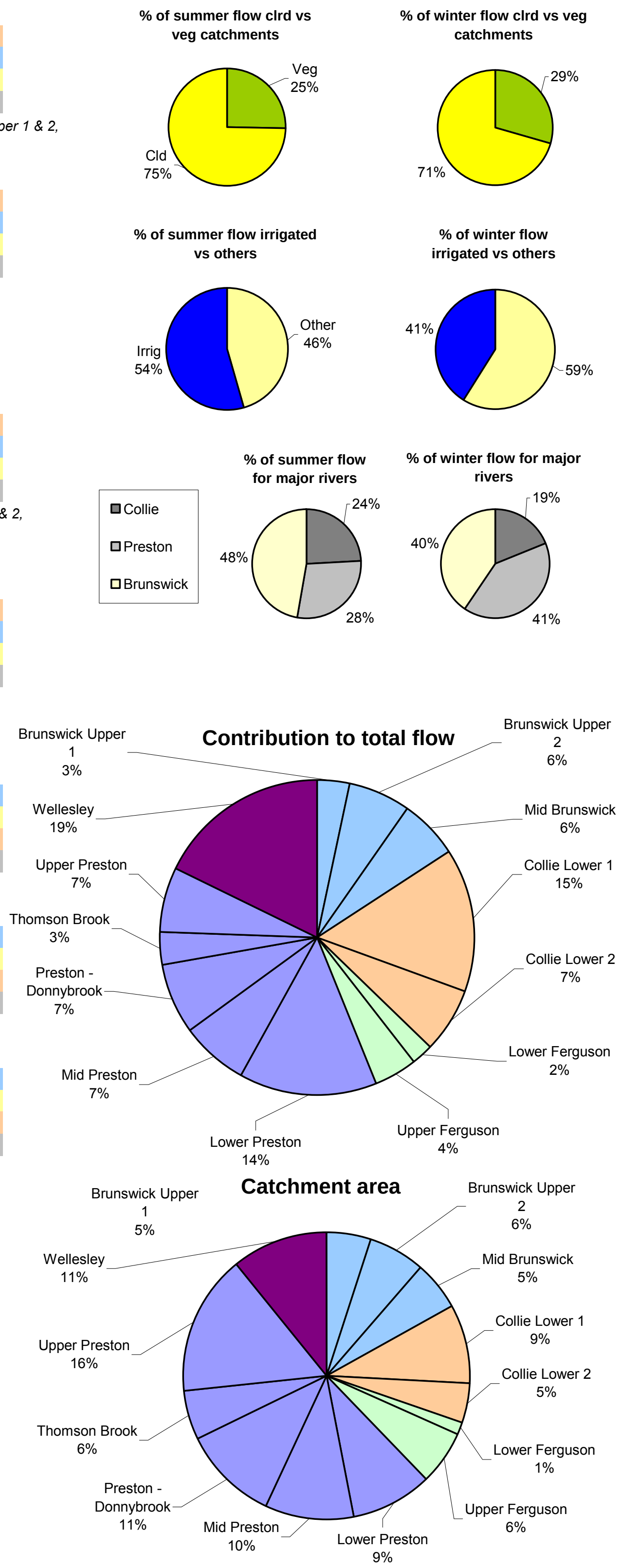


Figure 5.8 Discharge summary for winter (June–August) and summer (January–February)

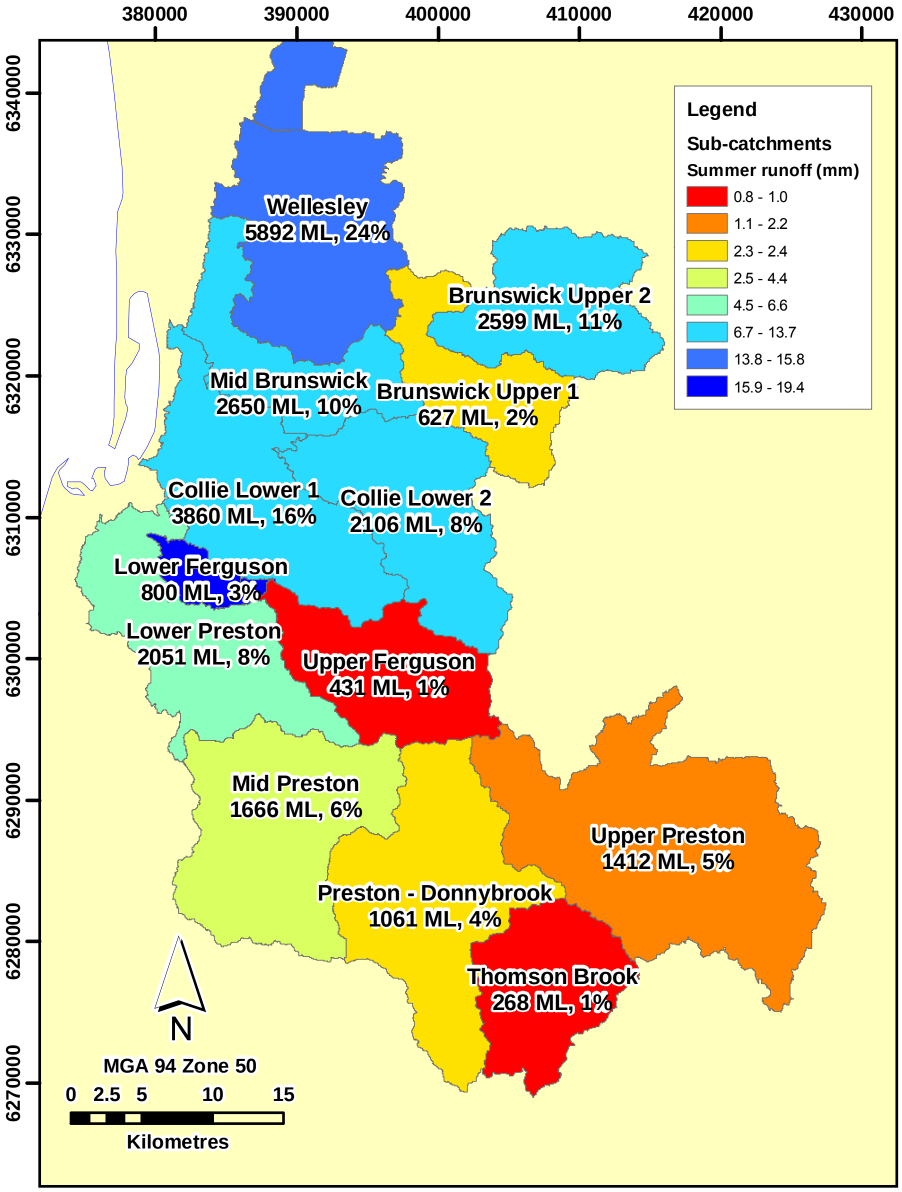


Figure 5.9 Average summer discharge and runoff (December–February)

6. Future modelling

Before conducting further modelling work, revision of input data will be undertaken. As a minimum this will include:

- Field validation of catchment boundaries to assess connectivity of some drains which could not be identified accurately from aerial photography and the LiDAR DEM.
- Review of discharge time-series on the Brunswick River gauge 612047.

The next step in the modelling process is to implement the current model in the more robust WaterCAST framework (the Water and Contaminant Analysis and Simulation Tool) (http://www.toolkit.net.au/WaterCAST), which is part of eWater CRC Catchment Modelling Toolkit. WaterCAST is a flexible catchment modelling framework which allows hydrological simulations to be coupled with a nutrient export model, resulting in more realistic quantification of nutrient loads than the Catchment Management Support System (CMSS).

WaterCAST has optional functionality which can be implemented to assess various landuse, re-vegetation and climatic scenarios. This includes in-stream and pass-through nutrient and sediment filters, a riparian nitrogen model, and a riparian particulate model. Modification to spatial input datasets can be undertaken to assess the impacts of land-use change.

Synthetic time-series will be used to drive the hydrological model for climate change scenarios. Rainfall and potential evapotranspiration time-series will be sourced from Bureau of Meteorology or CSIRO, or generated by the Water Science Branch modelling team using stochastic climate modelling.

Potential scenarios to be modelled have been outlined in the document *Nutrient export modelling of the Leschenault catchment* (Kelsey, 2009) and have been included below in Table 7.1. Input data requirements for model scenarios are discussed briefly below.

Table 6.1 Possible scenarios to be modelled by WaterCAST

Scenario	Implemenatation
Urban Expansion	With soil amendment, without soil amendment.
Changes in Land Use	Intensification of dairies and horticulture.
Dairy Effluent Management	Model dairies with current effluent management and proposed improvements.
Point Source Management	Requires point source mapping and estimations of flow, TN and TP outputs from each point source. Model point source removal.
Riparian Management	Estimate changes following riparian zone management, and estimate area of riparian zone required to make significant change to exports.
Fertiliser Action Plan	Update current modelling
Application of soil amendment	Update current modelling
Climate Change	Examine changes to river inflows to estuary with various climate change scenarios

Urban expansion

Spatial data of the potential urban expansion areas are readily available. However in Western Australia the effectiveness of the various urban BMPs designed to reduce nutrient pollution are unknown. This means that the modelling predicts the changes to nutrient export that would result from “conventional “ urban development. This is thought to be the worst-case scenario.

Changes in land use – intensification of dairies and horticulture

This is easily modelled if the required changes are specified.

Dairy effluent management

The data required includes, for each dairy, the number of cows, the current effluent management practices and the proposed effluent management practices.

Point source management

All the nutrient point sources within the catchment need to be mapped and nutrient outputs and disposal methods known.

Riparian management

The locations of all areas of riparian zone management need to be specified. The management actions need to be specified: fencing, stock exclusion, revegetation. The effectiveness of riparian zone management in Western Australia is still being researched, with different results in different locations. The modelling approach is to specify exactly the underlying assumptions, so that if these change the modelling can be easily updated.

Climate change

To estimate future climate change, the Intergovernmental Panel on Climate Change (IPCC 2000) prepared 40 greenhouse gas and sulfate aerosol emission scenarios for the 21st century that combine a variety of assumptions about demographic, economic and technological driving forces likely to influence such emissions in the future. The two climate change scenarios that are generally modelled are:

- **B1 scenario:** The population peaks around 2050 and declines thereafter. There is an emphasis on global solutions to economic, social, and environmental sustainability, including the introduction of clean efficient technologies. This is an optimistic scenario.

- **A2 scenario:** The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge slowly, leading to steadily increasing population and per capita economic growth. Technological changes are more fragmented and slower than in other scenarios. The A2 scenario is the highest emission option (pessimistic scenario) with continued high rates of greenhouse gas emissions that reach 1.7 times current levels by 2090.

7. Conclusions

The work conducted to date was focused on developing and calibrating a model capable of simulating the water-balance in the Leschenault catchment for current conditions.

Calibration of the flow model indicated that it was a moderately good predictor of discharge behaviour at monthly time step in the Leschenault catchment, with Nash-Sutcliffe efficiencies of between 0.69 and 0.92 for all catchments, and a good fit for seasonal dynamics.

The model allowed quantification of flows in the major rivers in the Leschenault catchment, and identified the following points regarding the catchment hydrology:

- the Darling Plateau catchments contribute less discharge annually than the cleared coastal plain catchments
- the Collie and Brunswick catchments contribute more discharge than the Preston River and Ferguson River catchments
- all catchments experience a disproportionate reduction in discharge when rainfall decreases
- in dry years, discharge reduces comparatively more in heavily vegetated catchments when compared to cleared catchments
- the relative proportion of flow from irrigated catchments increases in summer
- irrigation return flows make a significant contribution to the water-balance of the Leschenault catchment in summer

Further development will combine the flow model, and nutrient modelling to examine the influence of climate and land use changes in the Leschenault catchment.

8. References

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Zhang, L, Hickel, K & Shao, Q 2005, ‘Water balance modelling over variable time Scales’. In Zerger, A & Argent, RM (eds), *MODSIM 2005 International Congress on Modelling and Simulation*, Modelling and Simulation Society of Australia and New Zealand, December 2005, pp. 2988–2994.

Appendix A. Model equations

Monthly water-balance model (*Zhang et al., 2005*)

Equations:

$$PT\ (t) = P\,(t) + I\,(t)$$

$$X(t) \quad = PT(t)\left(1 + \frac{(S_{\max} - S(t-1) + E_0(t))}{PT(t)} - \left[1 + \left(\frac{(S_{\max} - S(t-1) + E_0(t))}{PT(t)} \right)^{\alpha_1} \right]^{1/\alpha_1} \right)$$

$$W(t) = X(t) + S(t-1)$$

$$E(t) = W(t)\left(1 + \frac{E_0(t)}{W(t)} - \left[1 + \left(\frac{E_0(t)}{W(t)} \right)^{\alpha_2} \right]^{1/\alpha_2} \right)$$

$$Q_d(t) = P(t) + X(t)$$

$$Y(t) = W(t)\left(1 + \frac{E_0(t) + S_{\max}}{W(t)} - \left[1 + \left(\frac{E_0(t) + S_{\max}}{W(t)} \right)^{\alpha_2} \right]^{1/\alpha_2} \right)$$

$$R(t) = W(t) - Y(t)$$

$$S(t) = Y(t) - E(t)$$

$$G(t) = (1-d)G(t-1) + R(t)$$

$$Q_b(t) = dG(t-1)$$

$$Q(t) = Q_b(t) + Q_d(t)$$

Where:

P(t) = precipitation at time (t)

PT =precipitation total

S_{max} = maximum groundwater store

W = water availability

Y = evapotranspiration opportunity

E = evapotranspiration

Q_b =groundwater discharge (baseflow)

I = irrigation

X = state variable

E_0 = evaporation potential

Q_d = direct runoff

R = groundwater recharge

G = groundwater store

α_1, α_2 = fitting parameters

Altered monthly water-balance model

Equations:

$$I_r(t) = \begin{cases} I(t) I_w \left(\dfrac{E_0(t)}{ET_w} \right) & E_0 < ET_w \\ I(t) I_w & E_0 > ET_w \end{cases}$$

$$X(t) = P(t)\left(1 + \frac{(S_{\max} - S(t-1) + E_0(t))}{P(t)} - \left[1 + \left(\frac{(S_{\max} - S(t-1) + E_0(t))}{P(t)} \right)^{\alpha_1} \right]^{1/\alpha_1} \right)$$

$$W(t) = X(t) + S(t-1)$$

$$E(t) = W(t)\left(1 + \frac{E_0(t)}{W(t)} - \left[1 + \left(\frac{E_0(t)}{W(t)} \right)^{\alpha_2} \right]^{1/\alpha_2} \right)$$

$$Q_d(t) = P(t) + X(t)$$

$$Y(t) = W(t)\left(1 + \frac{E_0(t) + S_{\max}}{W(t)} - \left[1 + \left(\frac{E_0(t) + S_{\max}}{W(t)} \right)^{\alpha_2} \right]^{1/\alpha_2} \right)$$

$$R(t) = W(t) - Y(t)$$

$$S(t) = Y(t) - \beta E(t)$$

$$Q_b(t) = \begin{cases} d(G(t-1) - G_{RB}), & G(t-1) > G_{RB} \\ 0, & G(t-1) < G_{RB} \end{cases}$$

$$G(t) = G(t-1) - Q_d(t) + R(t) - (1-\beta)E(t)$$

$$Q(t) = Q_b(t) + Q_d(t) + I_r$$

$$Efficiency = 1 - \frac{\sum_{t=1}^{T} (Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T} (Q_o^t - \overline{Q}_o)^2}$$

Where:

Ir = irrigation return flow parameter

Iw = Irrigation weighting

Qo=Observed discharge

Qm=Modelled discharge

ETw = irrigation evapotranspiration weighting parameter

Appendix B. Summary of results

Gauge ID	Catchment	Veg %	Area (km^2)	Average Annual Flow (ML)	Average Winter Flow (ML) May - Oct	Average Summer Flow (ML) Nov-Apr	Average Annual Yield (mm)	Average Winter Flow (mm) May - Oct	Average Summer Flow (mm) Nov-Apr	Average Annual Irrigation (mm)	Average Annual Irrigation (ML)	Average Annual Rainfall (mm)	% of Total Discharge	Average Summer Flow (ML) Dec-Feb	Average Winter Flow (ML) Jun-Aug	% of Total Discharge Summer Dec-Feb	% of Total Discharge Winter Jun-Aug	Average Annual Irrigation Return Flow (ML)	Average Annual Irrigation Return Flow (mm)
611004	Mid Preston	64%	186	20 082	18 417	1 666	108	99	9			850	7%	823	13 741	6%	7%		
611006	Preston - Donnybrook	44%	195	20 447	19 386	1 061	105	99	5			835	7%	460	13 634	4%	7%		
611007	Lower Ferguson	7%	23	6 134	5 334	800	267	232	35	108	2 489	835	2%	445	4 078	3%	2%	555	24
611009	Upper Preston	72%	289	19 014	17 595	1 419	66	61	5	3	945	792	7%	650	12 009	5%	6%	567	2
611010	Lower Preston	27%	164	40 044	37 994	2 051	244	232	13	8	1 318	828	14%	1 088	30 092	8%	16%	293	2
611017	Upper Ferguson	62%	114	12 115	11 684	431	106	102	4			855	4%	90	8 275	1%	4%		
611111	Thomson Brook	75%	102	8 912	8 644	268	87	85	3			811	3%	98	6 093	1%	3%		
612022	Brunswick Upper 2	90%	117	17 712	15 113	2 599	151	129	22			885	6%	1 383	9 643	11%	5%		
612032	Mid Brunswick	35%	98	17 492	14 843	2 650	178	151	27	63	6 214	885	6%	1 346	10 347	10%	5%	1 644	17
612039	Wellesley	18%	199	50 212	44 320	5 892	252	223	30	94	18 629	933	18%	3 144	33 731	24%	18%	3 911	20
612043	Collie Lower 2	16%	83	19 446	17 340	2 106	234	209	25	2	186	881	7%	1 055	11 693	8%	6%	57	1
612046	Collie Lower 1	21%	164	41 486	37 626	3 860	253	229	24	66	10 879	840	15%	2 065	29 605	16%	16%	2 336	14
612047	Brunswick Upper 1	67%	93	9 409	8 783	627	101	94	7			885	3%	218	5 841	2%	3%		